



IRSTI 67.01.81

Article

<https://doi.org/10.32523/2616-7263-2026-154-1-35-48>

## Digital simulation of soil sieve analysis: visualization of the laboratory process and practical relevance

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**Abstract.** This paper presents approaches for enhancing the accuracy and methodological transparency of laboratory determinations of soil grain-size distribution using digital simulation. The study aims to develop and implement an interactive model of the sieve analysis process that visualizes the sequence of laboratory operations and highlights the importance of a standardized procedure. The scientific significance lies in formalizing the traditional testing methodology and creating an algorithm that enables precise reproduction in a digital environment. The practical relevance of the research stems from the simulation's ability to compensate for the limitations of real laboratory conditions, where alternative sieving scenarios cannot always be reproduced, thereby reducing the accuracy and repeatability of results. This issue is critical not only in education but also in engineering practice, where insufficient sieving completeness may distort grain-size characteristics and, consequently, lead to errors in construction design and bearing-capacity assessment. Incorporating these aspects into the digital simulation improves methodological awareness. It expands its applicability to both academic and engineering contexts, providing an additional tool for quality control and strengthening the reliability of geotechnical decision-making.

**Keywords:** grain-size distribution, sieve analysis, soil testing, digital simulation, laboratory methodology.

## Introduction

Soil grain size distribution is one of the key indicators determining the engineering-geological and construction properties of soil [1-2]. The distribution of particles by size determines the filtration characteristics, density, compactability, water permeability, and behavior of soil under load [3]. Therefore, sieve analysis, traditionally used in laboratory practice, occupies a central place in the training program for future construction specialists. Despite its simplicity, the sieving technique has several aspects that directly affect the accuracy of the results obtained and the correctness of the subsequent engineering interpretation [4].

Today, many studies examine the effectiveness of various scenarios, methods, and tools for soil granulometry [5-7]. This study analyzes the possibilities of mathematical modeling to describe the particle size distribution (PSD) of soils, which is an important source of information about the gradation and distribution of particle sizes. The authors [8] compare the predictive capabilities of three groups of mathematical models, selecting the nine most robust and proven options from previous studies. The evaluation uses 144 experimental data sets across 12 soil texture classes from the UNSODA database. Attention was paid to the models' ability to predict values at points not included in the sample, which is key to correctly restoring the shape of the PSD curve. To do this, a comprehensive ranking method and relative error assessment were used to compare the effectiveness of models on different texture classes. The results showed that the number of the model's parameters is not directly related to the accuracy of predictions. The Skaggs and Weipeng models demonstrated the best results in interpolation and extrapolation. Thus, the study emphasizes the importance of choosing the correct function when analyzing different types of soils.

In the following work, [9] proposes an improved mechanical method of washing and sieving to obtain an accurate particle size distribution of soil. The developed technology is an extension of the previously created manual method of «extended wet sieving» and is based on the modernization of a traditional vibrating sieving machine. The improved design includes steel sieves with a mesh size of 0.063 mm and ten fabric sieves with apertures ranging from 0.048 to 0.0008 mm, which allows for effective separation of silt and clay particles. The machine generates three-dimensional movement and vibration, ensuring the rapid passage of particles smaller than the sieve apertures.

The authors propose utilizing machine learning to enhance the accuracy and reproducibility of estimates. To determine the applicability of existing approaches, the researchers [10] conducted a comparative study that assessed the effectiveness of eleven mathematical models and three machine learning algorithms previously used to analyze soils in the northwestern Himalayan region. Such a comparative analysis was necessary because a correct model must adequately describe the entire PSD curve for different soil types. The quality of the selection was assessed using standard criteria: the adjusted coefficient of determination, the Akaike information criterion, and the root mean square error. The most accurate results among the mathematical models were shown by the Fredlund, Weibull, and Rosin–Ramler models, while the Gompertz, S-curve, and Van Genuchten models demonstrated an insufficient level of correspondence with the experimental data. Thus, the authors note that modern ML approaches have significant potential for PSD modeling, surpassing traditional mathematical functions in accuracy, especially when analyzing

complex soil samples.

In continuing the study, it should be noted that one of the equally important factors to consider is the completeness of sieving, the degree to which particles of different sizes are distributed across the sieves during the test [11-12]. In educational settings, students usually encounter only one scenario: a single sample is sieved, and a single particle-size distribution curve is obtained. However, a single observation does not allow the full sensitivity of the method to changes in testing conditions or possible deviations from the standard procedure to be identified. Acquiring skills in how significantly even a small violation of the completeness of sieving can affect the final shape of the curve, the classification of the soil, and, consequently, the choice of its application in construction.

Traditional laboratory work does not allow such changes to be fully demonstrated, since conducting several full-fledged tests within a single class requires significant time and labor resources. Repeated sieving, particularly under deliberately altered conditions leading to incomplete sieving, is not typically included in the teaching format and is rarely performed. As a result, only a single reference outcome is observed, without comparison to alternative results arising from procedural deviations that are common in real practice. This limits the depth of understanding of the method and reduces future engineers' ability to evaluate the reliability of the data obtained critically. In addition to the educational environment, the issue of complete sieving is also significant in industrial practice, especially when implementing large-scale construction and infrastructure projects. In conditions of large volumes of engineering-geological work, laboratory tests are often carried out in an accelerated mode, which simplifies individual stages of the methodology. These seemingly insignificant deviations can accumulate and affect the final assessment of soil properties.

### The methodology

The study included four key stages presented in Figure 1. The sequential implementation of these stages ensured the collection of reliable experimental data and its further use in the development of a digital model. Accordingly, the first stage of the study included laboratory determination of the soil particle-size distribution in accordance with the standard [13].

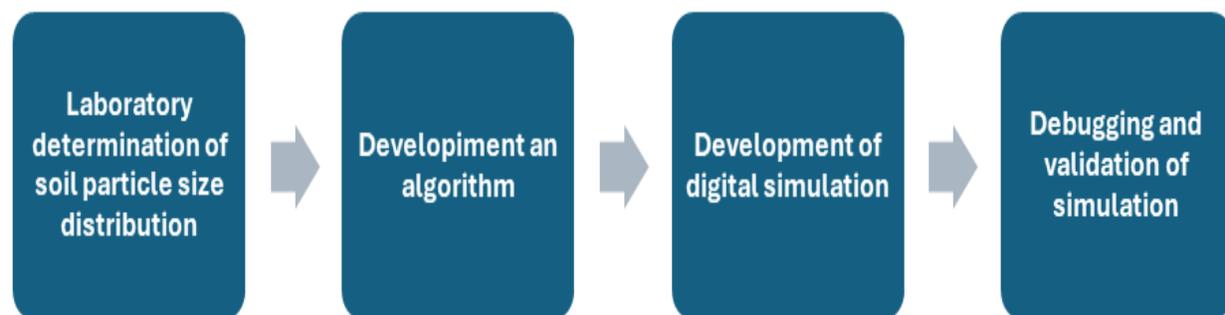


Figure 1. Research workflow

The laboratory setup included a complete set of soil-testing sieves with mesh openings ranging from 10 mm to 0.1 mm, arranged in descending order of aperture size. For weighing operations,

both analytical and technical laboratory balances were employed, the latter ensuring a relative weighing accuracy better than 0.1% (Figure 2).



Figure 2. Process of testing

Standard supporting equipment, such as a porcelain mortar and pestle with a rubber tip for gentle disaggregation of soil aggregates, a porcelain cup, a brush for cleaning the sieve surfaces, and auxiliary tools for sample handling, was also used [13-14]. All drying procedures were performed using a laboratory drying oven and a sand bath to ensure a constant mass of the soil sample before analysis. An average soil sample was prepared using the quartation method and subsequently dried to constant mass. The sieves were mounted in a vertical column and positioned on a receiving pan. The prepared sample was carefully placed onto the upper sieve and covered with a lid. Sieving was first performed manually through light lateral tapping of the sieve column until the passage of soil particles stabilized.

The fractions retained on each sieve were then collected sequentially, beginning from the uppermost sieve. To ensure complete disaggregation of soil aggregates, the retained material was gently ground in a porcelain mortar using a pestle with a rubber tip and reintroduced into the sieve column for repeated sieving. This step ensured that each grain-size fraction contained only individual particles rather than composite aggregates. The completeness of sieving was checked by shaking each sieve over a clean sheet of paper and visually confirming that no additional particles passed through. The mass of each retained fraction was determined using laboratory balances.

In the second stage of the study, the actual laboratory sieve analysis method was presented as an algorithm suitable for subsequent transfer to a digital environment. Based on the experimental protocol, the main operations, the sequence of actions performed, and the key control points directly affecting the particle size analysis result were identified. First, the sample preparation procedure was structured: actions for taring the tray, collecting soil, controlling the sample weight, and recording the initial parameters were defined. Next, the assembly of the sieve column was formalized, including the order of sieve arrangement by hole size, checking the weight of each empty sieve, and its identification in the system. The sieving process was presented as a sequence of actions: installing the column on a vibrating platform, starting and stopping the device, and

checking the completeness of the sieving. Attention was paid to steps that could lead to methodological deviations in real testing: the appearance of particles when shaking over a sheet of paper (incomplete sieving) or their absence (complete sieving). These situations were included in the algorithm as several scenarios. The final block of the formalized procedure included weighing the residue on each sieve, automatically constructing a table of fractional composition, and calculating the distribution of mass and pass percentages. Both variants of the incomplete and complete sieving scenarios were integrated into the structure, which made it possible to subsequently programmatically simulate the two modes of operation.

The digital simulation was developed using object-oriented programming technologies with ActionScript, which enabled the implementation of interactive elements, particle animation, and visual support for the stages of sieve analysis. The development environment used allowed for the creation of step-by-step user scenarios, including the selection of sieves, simulation of the sieving process, and automatic construction of a particle size distribution curve. The simulation was implemented as a low-resource application running in a standard IBM PC-compatible software environment. For it to work correctly, a basic computer configuration with an Intel Pentium 2 GHz processor and 256 MB of RAM is sufficient, which confirms the accessibility of the solution for educational audiences and allows it to be used on a wide range of devices.

Simulation debugging included verifying the correctness of the sieving algorithm, comparing calculated values with laboratory test results, and evaluating operational stability across various scenarios (complete and incomplete sieving). The logical sequence of stages and the correctness of the recalculation of the mass fractions were checked.

### Findings/Discussion

Based on the sieve analysis performed, a distribution of fractions was obtained that characterizes the soil's structural features. The masses of soil fractions are presented in Figure 3. 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.

Particle size, mm	Percent passing, %
10	90.04
5	80
2	68.06
1	54
0.5	21.08
0.25	16.1
0.1	7.06
0.05	0

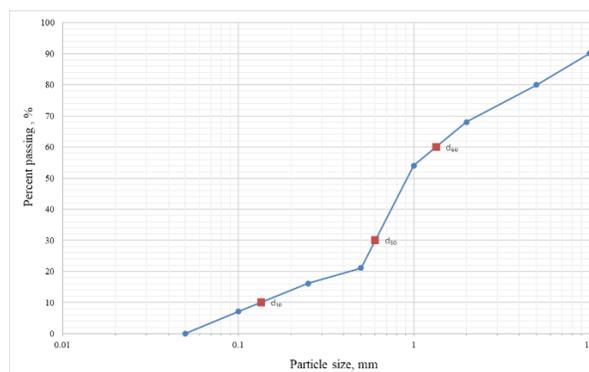


Figure 3. Particle size distribution: experimental data

The developed algorithm for the laboratory sieve analysis method, to be subsequently transferred to a digital environment, is shown in Figure 4.

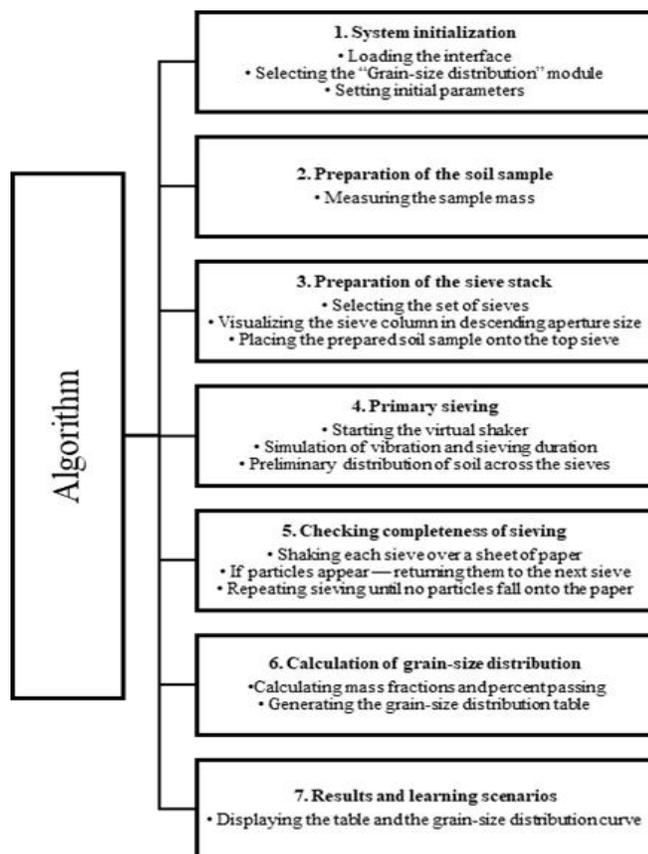


Figure 4. Algorithm for soil sieve testing

The algorithm reflects the sequence of operations performed when determining the granulometric composition of soil and serves as a basic model for subsequent digital implementation.

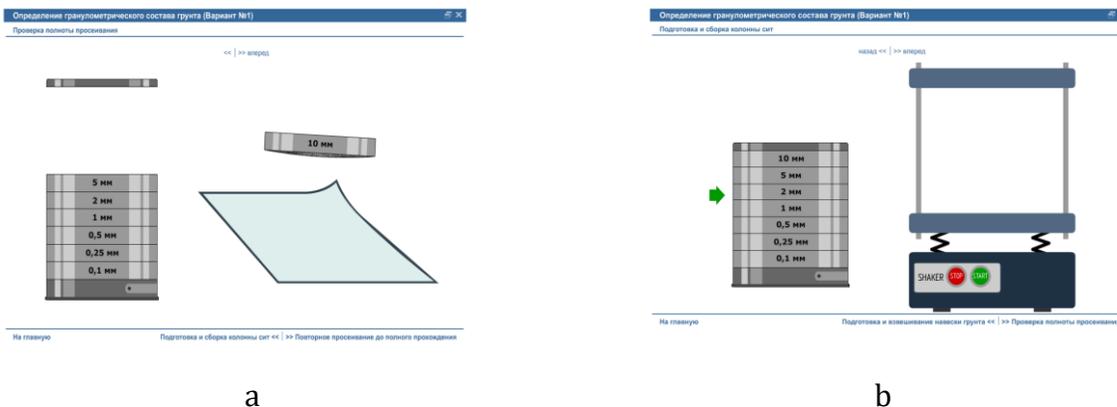


Figure 5. Test version of digital simulation: a) verification of sieving completeness; b) during the testing procedure [15]

Each stage of the algorithm is highlighted as a separate technological procedure, which ensures the accuracy and reproducibility of the description of the actual laboratory process. Such detail eliminates the variability that arises when tests are performed by different operators and establishes uniform requirements for the sequence of actions. Visualization helps to identify the stages that are critical for visualization in the simulation, including checking the completeness of sieving and processing residual particles. Based on this, the functional modules of the digital model and the logic of transitions between them were established. As a result, the algorithm ensured the correct transformation of the traditional methodology into an interactive digital format designed for educational and practical purposes. The developed digital simulation, based on experimental data and allowing the reproduction of various sieving scenarios, is shown in Figure 5.

Simulation allows soil testing and study of the methods of complete sieving and incomplete sieving, in which some fractions are retained on the surface of the sieves, and some end up on a sheet of paper after testing. This opportunity is significant for students, allowing them to obtain and compare two such results simultaneously. The debugging results showed that the simulation correctly reproduces the sieve analysis algorithm. The shape of the particle size distribution curve also fully corresponded to the laboratory curve. The interface modules worked stably during repeated actions, and transitions between simulation stages were performed without interruptions. Thus, the experimental digital simulation demonstrated stability, reliability of results, and readiness for use in educational and demonstration practices..

Table 1. Methodological Value of the Simulation

№	Scenario	Potential consequences	Methodological value of the simulation
1	Particles are not transferred to the next sieve after shaking above the paper	Underestimation of fine fractions, distorted particle size distribution, and incorrect soil classification	The simulation demonstrates that incomplete particle transfer results in inaccurate fraction distribution.
2	Particles are transferred to the next sieve, but repeated sieving is omitted	Fine particles remain trapped; overestimation of coarse fractions	The simulation illustrates the effect of incomplete sieving on the final particle size distribution.
3	The sieving completeness check in the paper is omitted	High risk of systematic error; misrepresentation of grain-size composition	The simulation visualizes the critical role of sieving completeness verification.
4	Completeness verification is performed for only one sieve, while others are ignored	Irregular errors in individual fractions; inconsistent results	The simulation emphasizes the necessity of verifying every sieve in the set.
5	Shaking above the paper is performed for an insufficient duration	Residual particles remain; slight systematic overestimation of coarse fractions	The simulation reveals measurable differences between full and incomplete sieving.

One of the key results of the development is the ability to demonstrate the complete procedure for checking the completeness of sieving. In traditional laboratory conditions, students often work with soils that either pass completely through the sieve on the first cycle or contain a minimal amount of residue. In such cases, students do not have the opportunity to observe an alternative scenario — the appearance of particles on a sheet of paper when checking the completeness of sieving and the need to return them to the next sieve for subsequent re-sieving. As a result, an important methodological element of the procedure goes unnoticed, although it is precisely this element that ensures accuracy and prevents material loss. The developed simulation compensates for this limitation of real laboratory practice by allowing both scenarios, complete and incomplete sieving, to be reproduced, regardless of the properties of a particular soil sample. This expands the educational potential of the methodology and ensures the mastery of the critically important stage of checking the completeness of sieving.

The developed simulation accurately reproduces the standardized stages of the sieve analysis procedure, visualizing each step in accordance with the requirements of the standard methodology. This enables the user to clearly observe how the completeness check is performed, how particles are redistributed, and why repeated verification is essential to the process. Such detailed visualization serves as a preventive function, helping to avoid typical mistakes that are frequently made during the first independent execution of the test. The scenarios presented in Table 1 illustrate the potential consequences of deviations from the standardized procedure, while the simulation acts as a tool for giving a consistent understanding of the correct sequence of operations and their impact on the final grain-size distribution

From a methodological point of view, the simulation highlights two important aspects:

- The accuracy of sieve analysis depends not only on the equipment, but also on the operators' compliance with the regulated procedure.
- The lack of sieving completeness control is a source of systematic errors that are difficult to detect and diagnose by indirect signs.

Thus, simulation serves as a tool for teaching the accuracy of laboratory testing, minimizing material losses, and improving the quality of particle size distribution determination. This makes it a significant element in the training of future builders, developing both technical skills and engineering thinking based on an understanding of the cause-and-effect relationships between test quality and the reliability of engineering solutions. Moreover, simulation expands not only the educational but also the practical professional scope of application, helping to reduce risks when making engineering decisions at the stages of research, design, and quality control of work.

## **Conclusion**

A digital simulation of soil sieve analysis was developed based on experimental data and the algorithmization of the laboratory procedure. The model reproduces the key stages of the methodology, including verification of the completeness of sieving, which often remains out of sight of students in normal laboratory conditions. The simulation demonstrates the impact of correct operation on the final distribution of fractions and promotes a better understanding of the standardized process. The resulting tool expands the possibilities of training and can serve as a basis for further improvement of digital techniques in engineering practice. Research conclusions:

- Algorithmic modeling of the methodology allowed the identification of key stages of sieve analysis and the assessment of their influence on result reliability.
- The use of ActionScript provided flexibility in visualization and the ability to create a step-by-step interactive model without reducing computational accuracy.
- Debugging of the simulation showed its resistance to variable scenarios and demonstrated the value of the digital tool for ensuring the correct execution of the laboratory process.

**Funding:** This research has been/was/is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP26195121 «Development of an educational digital platform for future builders with simulation of construction processes and integration with measuring devices via IoT»).

### **The contribution of the authors:**

Tulebekova A. – development of the research concept, critical review of content.

Denissova N. – verification of the developed simulation module.

Kastrati B. – review of sources

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### **Цифрлық топырақ елеу симуляциясы: зертханалық үдерісті визуализациялау және практикалық маңыздылығы**

**Аңдатпа.** Мақалада топырақтың гранулометриялық құрамын зертханалық жағдайда анықтаудың дәлдігі мен әдістемелік айқындығын арттыруға бағытталған цифрлық симуляцияны қолдану тәсілдері қарастырылады. Зерттеудің мақсаты – елеу талдауындағы зертханалық операциялардың дәйектілігін визуализациялайтын және стандартталған

процедураның маңызын көрсететін интерактивті модельді әзірлеу және енгізу. Жұмыстың ғылыми маңыздылығы дәстүрлі сынақ әдістемесін формализациялауға және оны цифрлық ортада дәл қайта жаңғыртуға мүмкіндік беретін алгоритмді жасауға негізделген. Практикалық маңыздылығы – нақты зертханалық жағдайда балама елеу сценарийлерін әрдайым орындау мүмкін еместігіне байланысты симуляцияның бұл шектеулерді өтеу қабілетінде, бұл нәтижелердің дәлдігі мен қайталанғыштығын төмендетеді. Бұл мәселе тек білім беру саласында ғана емес, инженерлік тәжірибеде де өзекті, себебі елеудің толық орындалмауы гранулометриялық сипаттамалардың бұрмалануына, сондай-ақ негіздерді жобалаудағы және көтергіштік қабілетін бағалаудағы қателіктерге әкелуі мүмкін. Осындай аспектілердің цифрлық модельге енгізілуі әдістемелік түсініктілікті арттырып, оның оқу және инженерлік ортадағы қолданылу аясын кеңейтеді және сапаны бақылаудың қосымша құралы ретінде геотехникалық шешімдердің сенімділігін күшейтеді.

**Түйін сөздер:** гранулометриялық құрам, елеу талдауы, топырақ сынақтары, цифрлық симуляция, зертханалық әдістеме.

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### **Цифровая симуляция ситового анализа грунта: визуализация лабораторного процесса и практическая значимость**

**Аннотация.** В статье представлены подходы к повышению точности и методической прозрачности лабораторного определения гранулометрического состава грунта с применением цифровой симуляции. Цель исследования заключается в разработке и внедрении интерактивной модели процесса ситового анализа, позволяющей визуализировать последовательность лабораторных операций и подчеркнуть важность соблюдения стандартизированной процедуры. Научная значимость работы заключается в формализации традиционной методики испытаний и создании алгоритма, обеспечивающего её точное воспроизведение в цифровой среде. Практическая значимость связана со способностью симуляции компенсировать ограничения реальных лабораторных условий, при которых альтернативные сценарии просеивания не всегда могут быть воспроизведены, что снижает точность и повторяемость результатов. Данный аспект важен не только в образовательной среде, но и в инженерной практике, так как недостаточная полнота просева может привести к искажению истинных значений гранулометрических характеристик грунта и привести к ошибкам в проектировании оснований и оценке несущей способности. Включение этих аспектов в цифровую модель повышает методическую осознанность и расширяет её применимость как в учебных, так и в профессиональных инженерных контекстах, являясь дополнительным инструментом контроля качества и повышения надежности геотехнических решений.

**Ключевые слова:** гранулометрический состав, ситовый анализ, испытание грунтов, цифровая симуляция, лабораторная методика.

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