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Coarse-grained soils compaction at the experimental site during the safe construction of the earthen dam

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Abstract. Achieving a high degree of compaction in coarse-grained soils is a critical requirement for ensuring the stability, safety, and long-term performance of earth dams. This study presents the results of comprehensive laboratory and field investigations aimed at identifying the optimal technological parameters for compaction of coarse-grained soils used in hydraulic embankment construction. The influence of grain-size distribution, fine fraction content, and compacted layer thickness on the achieved dry density was systematically investigated. Laboratory experiments were performed using the standard Soyuzdornii compaction apparatus and a vibration compaction device with a cylindrical mold of 300 mm in diameter. Field investigations were conducted at an experimental test site using a 27-ton SANY vibratory roller with compacted layer thicknesses of 50, 70, and 80 cm. The experimental results demonstrated that the highest dry density was achieved for a compacted layer thickness of 50 cm, whereas increasing the layer thickness reduced compaction efficiency due to the limited transmission of vibratory energy throughout the embankment. Furthermore, the proposed grain-size modelling approach was validated by comparing laboratory and field test results, confirming its applicability for reproducing the mechanical behaviour of natural coarse-grained soils under controlled laboratory conditions. The findings provide practical recommendations for selecting rational compaction parameters and can be applied in the design and construction of earth-filled hydraulic structures to improve embankment quality, structural reliability, and long-term operational performance.
Keywords: construction, coarse-grained soils, earthen dam, excavation, grain composition, model mixtures, industrial and environmental safety

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1. INTRODUCTION

At present, the construction of high earth dams remains one of the most important areas of hydraulic engineering. The reliability and long-term performance of such structures largely depend on the quality of embankment construction, where coarse-grained soils constitute the major portion of the dam body. Owing to their high strength, excellent drainage capacity, and the availability of local materials, these soils are widely used in the construction of rockfill and earth-rock dams, transportation embankments, and other critical geotechnical structures [1-3].

One of the most important technological stages in dam construction is soil compaction. The degree of compaction has a decisive influence on the strength, deformation, and hydraulic characteristics of the material. Insufficient compaction may lead to differential settlements, increased permeability, localized deformations, and a reduction in the long-term operational reliability of the structure [2–4].

Despite the considerable number of studies devoted to the mechanical behavior of coarse-grained soils, the selection of optimal compaction parameters remains an important research challenge [5]. Significant difficulties arise from the highly heterogeneous particle-size distribution, the presence of large rock fragments, and the inability to perform conventional laboratory tests without first developing representative scaled models of the natural material [6]. Therefore, there is a need to develop methodologies that ensure the comparability of laboratory and field investigation results [7].

Recent studies have demonstrated that compaction efficiency depends not only on the type of compaction equipment but also on the thickness of the compacted layer, the content of fine particles, the moisture content, the particle-size distribution, and the number of roller passes. A comprehensive consideration of these factors makes it possible to improve the quality of embankment construction and reduce the likelihood of operational defects during service [8-11].

The objective of the present study is to experimentally evaluate the influence of the principal technological parameters governing the compaction of coarse-grained soils, to develop a methodology for modeling their particle-size distribution, and to determine the optimal conditions for achieving maximum dry density during the construction of earth dams [12-13].

2. METHODS AND MATERIALS

2.1. Study Materials

The study focused on coarse-grained soils widely used in the construction of earth-filled hydraulic structures. Owing to their high shear strength, excellent drainage capacity, and resistance to external loading, these materials are extensively employed in the supporting prisms of rockfill and earth dams, where they play a key role in ensuring the overall stability and long-term performance of the structure [14-16].

Despite their widespread application, achieving the required degree of compaction remains one of the major engineering challenges associated with coarse-grained soils. This is primarily attributed to the considerable variability in grain-size distribution, the presence of large particles, and the difficulty of reproducing the natural structure of the material under laboratory conditions. Consequently, the identification of rational compaction parameters is essential for improving the mechanical performance, structural reliability, and service life of hydraulic earth structures [17].

The present study was undertaken to experimentally determine the optimum compaction conditions for coarse-grained soils through an integrated programme of laboratory and field investigations, with particular emphasis on evaluating the effects of grain-size characteristics and compaction technology on the achieved soil density [1, 18-19].

2.2. Materials

The investigated material consisted of coarse-grained soil obtained from a quarry designated as the primary source of construction material for the Pskem Hydropower Plant dam. The natural material comprised a heterogeneous mixture of boulders, cobbles, crushed stone, gravel, sand, and fine particles, with individual particle sizes reaching approximately 700-1000 mm.

Since laboratory testing of natural coarse-grained soils containing particles of this size is impractical using conventional testing equipment, model soil mixtures were prepared for the experimental programme. During the modelling process, the proportion of fine particles smaller than 5 mm was preserved, while the sizes of the coarser fractions were reduced proportionally in accordance with the adopted grain-size modelling procedure. This approach enabled the laboratory specimens to reproduce the granulometric characteristics of the natural material while satisfying the dimensional limitations of the testing equipment.

To evaluate the influence of fine fraction content on compaction behaviour, several model mixtures with different grain-size distributions were prepared and tested under identical laboratory conditions.

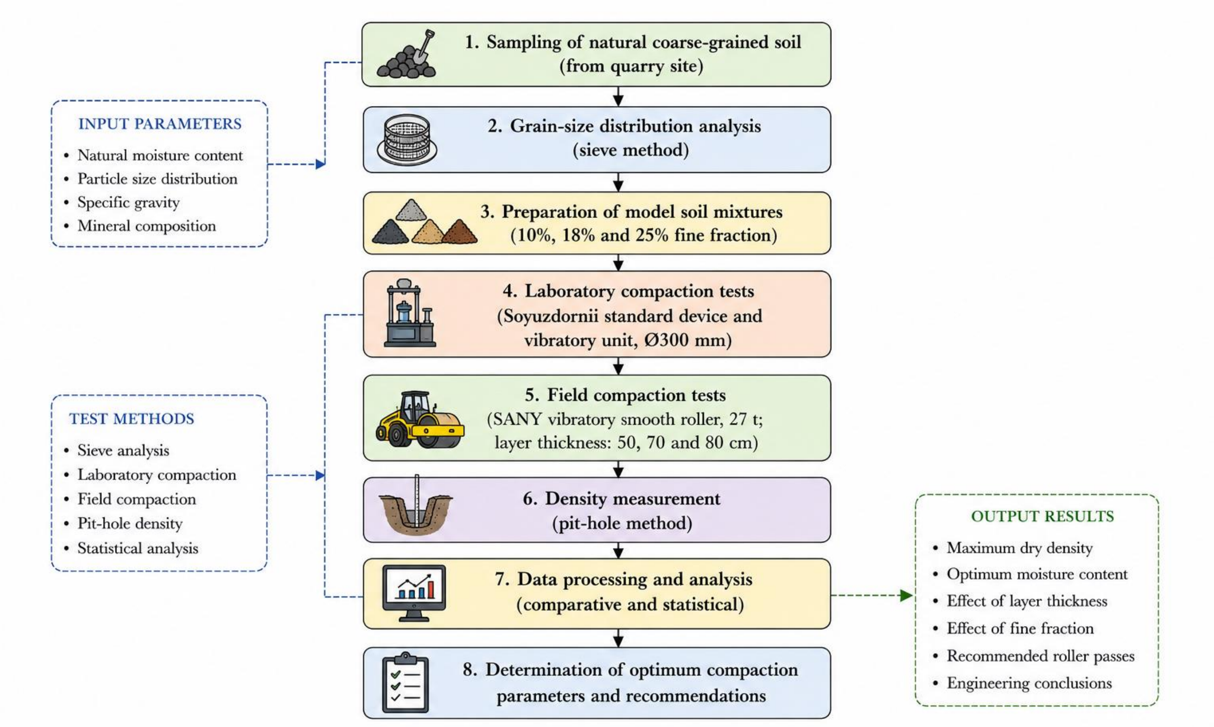


Fig. 1. Overview of the experimental program for investigating the compaction behaviour of coarse-grained soils, including specimen preparation, laboratory testing, field compaction, and data analysis.

2.3. Laboratory compaction tests

In laboratory conditions, two compaction methods were employed to determine the maximum dry density and optimum moisture content: the standard Soyuzdornii compaction method and the vibration compaction method using a laboratory device with a diameter of 300 mm. Because the original material contained particles up to 700-1000 mm, the grain-size composition was modelled according to the Gidroproekt procedure, limiting the maximum particle size to 60 mm while preserving the percentage of particles smaller than 5 mm [20].

The intermediate points of the model gradation curve were determined according to Equation (1).

$$P_m = (100 - p_{<5}) \cdot \frac{P_n}{100} + p_{<5} \tag{1}$$

Model mixtures containing 10–25% fine fraction were prepared and compacted to determine the relationship between fine fraction content and maximum dry density.

2.4. Field compaction tests

Prior to field testing, the vegetation layer was removed from a 100 × 100 m site, followed by grading and preliminary compaction using a 27-ton SANY vibratory roller. Experimental embankments were then constructed in layers of 50, 70 and 80 cm. Each layer was moistened (200 L/m³) and compacted using the same vibratory roller.

Compaction quality was monitored after every two roller passes using the pit-hole method. Moisture content and density were determined according to GOST 28514–90.

Fig. 2. Determination of the in-situ dry density of the first compacted layer using the pit-hole method after initial vibratory compaction.

2.5. Field Investigation

Field investigations were carried out at a specially prepared experimental site located within the construction area of the Pskem Hydropower Plant dam.

Prior to the field experiments, the vegetation layer was removed, after which the foundation surface was levelled and preliminarily compacted to provide uniform testing conditions. Experimental embankments with compacted layer thicknesses of 50, 70, and 80 cm were then constructed sequentially to evaluate the influence of layer thickness on compaction performance.

Compaction was performed using a 27-ton SANY single-drum vibratory roller. Before each compaction cycle, the soil was uniformly moistened to ensure consistent moisture conditions throughout the experimental programme. The in-situ density of each compacted layer was determined after every two roller passes using the pit-hole method in accordance with the requirements of GOST 28514–90. To improve the reliability and reproducibility of the experimental results, density measurements were conducted at several control locations within each test section.

2.6. Experimental Data Analysis

The experimental results were analysed using an integrated engineering approach that combined comparative evaluation of laboratory and field investigations, statistical analysis of the measured data, and assessment of the influence of the principal technological factors governing soil compaction.

Particular attention was given to evaluating the effects of compacted layer thickness, fine fraction content, and grain-size distribution on the maximum dry density achieved during compaction. The laboratory and field results were systematically compared to assess the consistency of the proposed testing methodology and to identify the parameters that most significantly influence compaction efficiency.

Furthermore, the obtained findings were interpreted in the context of recent advances in the mechanics of coarse-grained soils and modern embankment construction technologies. This comprehensive analysis made it possible to establish the optimum compaction parameters capable of achieving maximum dry density while maintaining the required strength and hydraulic performance of the compacted material [21-23].

3. RESULTS AND DISCUSSION

3.1. Evaluation of the Field Compaction Efficiency of Coarse-Grained Soils

The main objective of the field stage of the investigation was to evaluate the influence of compaction-related technological parameters on the achieved density of coarse-grained soil during earth dam construction. To address this objective, the experimental works were carried out at a specially prepared test site that closely simulated actual field construction conditions. Compaction was performed using a 27-ton SANY vibratory roller with the same number of roller passes for all test sections, which made it possible to minimize the influence of equipment operating conditions and focus primarily on the effect of compacted layer thickness [24-25].

The measurement results showed that the thickness of the compacted layer has a significant effect on the transmission of compaction energy and, consequently, on the achieved soil density. The highest density values were obtained for the 50 cm layer, whereas increasing the layer thickness resulted in a change in soil density due to the redistribution and attenuation of vibratory energy with depth [26].

The obtained results are presented in Table 1.

Table 1. Effect of compacted layer thickness on the achieved soil density.

Compacted layer thickness, cm	Dry soil density, t/m³	Relative change from the maximum value, %
50	2,19	0
70	2,13	–2,74
80	2,05	–6,39

As shown in Table 1, the highest dry soil density was achieved for a compacted layer thickness of 50 cm. Increasing the layer thickness to 70 cm resulted in a reduction in dry density of approximately 2.7%, whereas a further increase to 80 cm led to a decrease of more than 6% relative to the maximum value. These findings indicate that increasing the thickness of the compacted layer gradually reduces the efficiency of vibratory energy transmission throughout the soil mass, resulting in less effective compaction of the lower portions of the embankment [27-30].

Fig. 3 illustrates the relationship between compacted layer thickness and the achieved dry density of coarse-grained soil [31].

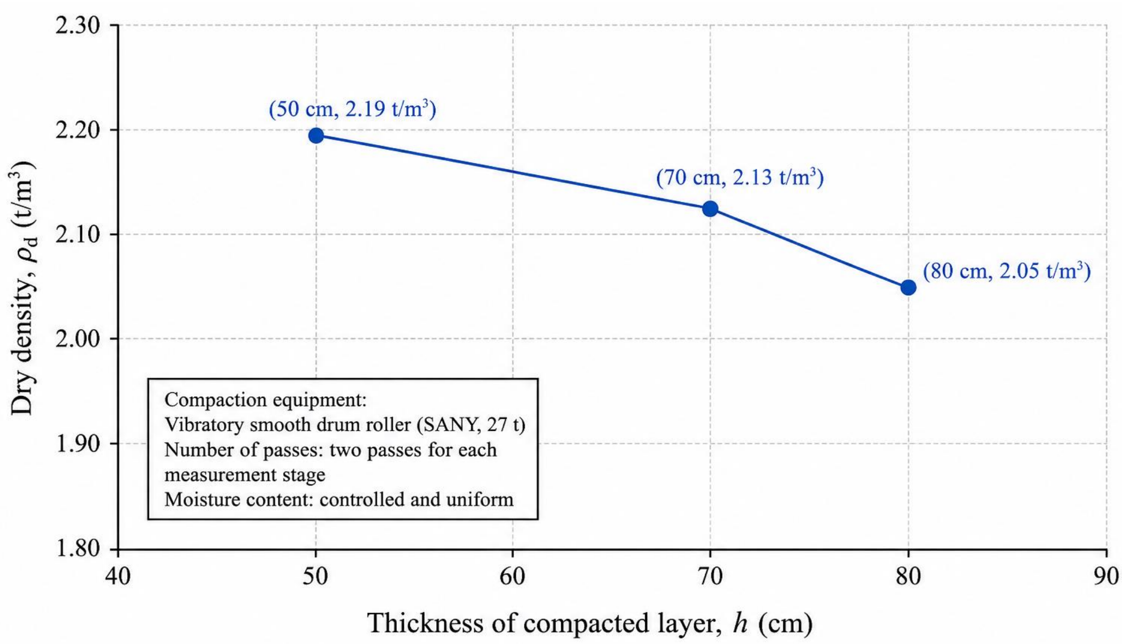


Fig. 3. Effect of compacted layer thickness on the achieved dry density of coarse-grained soil.

Analysis of the relationship presented in Fig. 3 indicates that the variation in dry soil density exhibits a non-linear trend with increasing compacted layer thickness. As the layer thickness increased from 50 cm to 70 cm, the reduction in dry density was relatively moderate. However, a further increase to 80 cm resulted in a more pronounced decrease in density, indicating a progressive decline in the effectiveness of vibratory compaction within the lower portion of the soil layer [32-34].

This behaviour can be attributed to the attenuation of vibratory energy as it propagates through the coarse-grained soil mass. A considerable proportion of the applied compaction energy is dissipated through particle rearrangement, interparticle friction, and the reorientation of coarse aggregates [35]. Consequently, as the compacted layer becomes thicker, the intensity of dynamic loading reaching the lower part of the layer decreases, preventing the entire soil mass from achieving a uniform degree of compaction. This process also increases the likelihood of residual voids and localized zones with insufficient density.

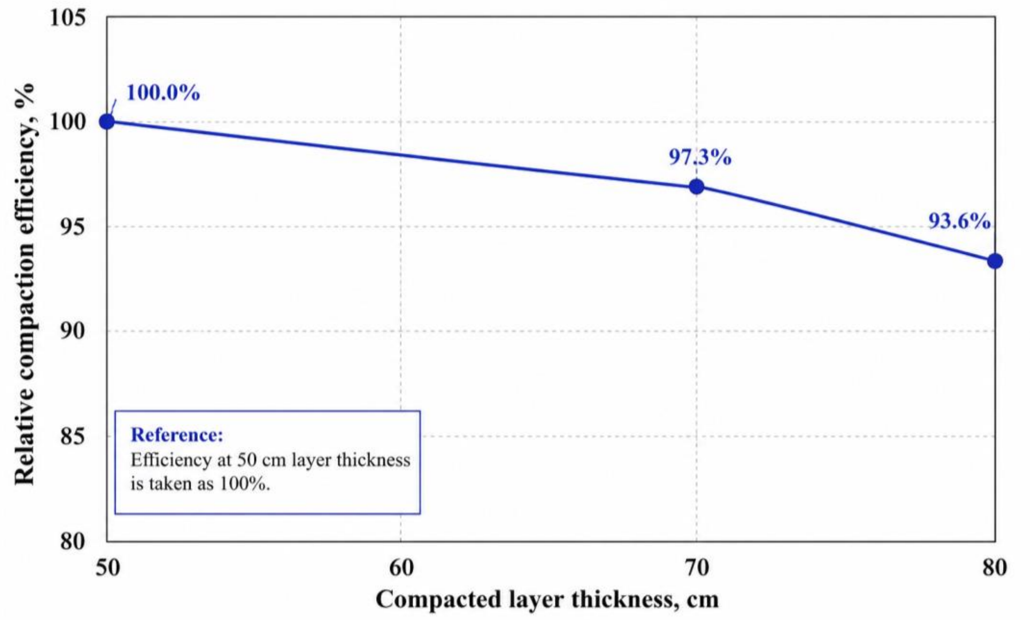


Fig. 4. Relative compaction efficiency versus compacted layer thickness.

To provide a normalized assessment of the influence of layer thickness, the relative compaction efficiency was calculated by taking the maximum dry density obtained for the 50 cm layer as 100%. As shown in Fig. 4, the relative efficiency decreased to approximately 97.3% for the 70 cm layer and to 93.6% for the 80 cm layer. Although the percentage reduction may appear moderate, even a small decrease in dry density can be important for high earth dams because it may correspond to a substantial volume of insufficiently compacted material across the entire embankment. The results confirm that increasing layer thickness reduces the ability of the vibratory roller to produce a uniformly compacted soil structure.

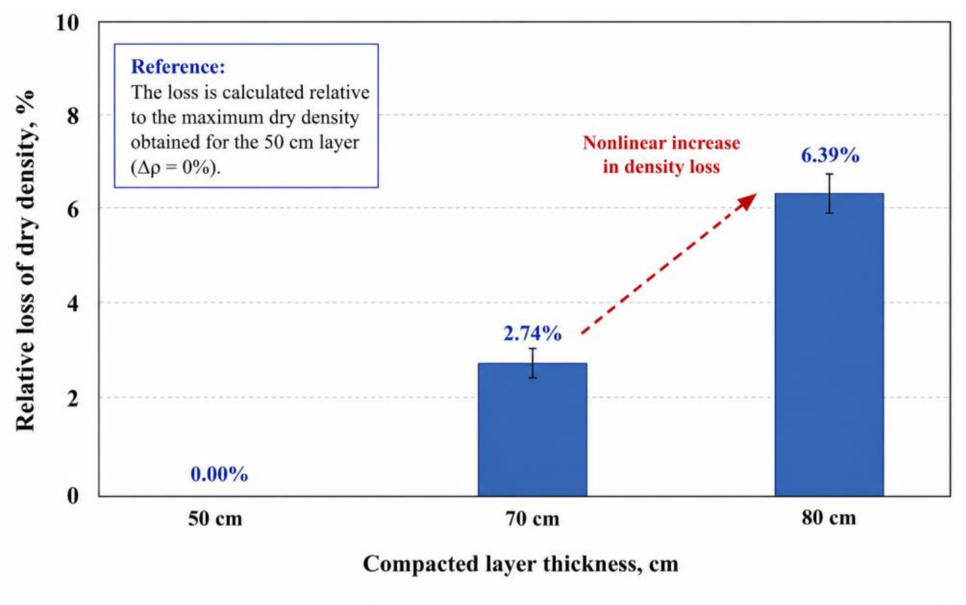


Fig. 5. Relative loss of dry density with increasing compacted layer thickness.

Fig. 5 presents the loss of dry density relative to the optimum result obtained for the 50 cm compacted layer. The density loss amounted to approximately 2.74% when the layer thickness was increased to 70 cm and 6.39% when it was increased to 80 cm. The disproportionately greater loss observed at 80 cm indicates that the relationship between layer thickness and compaction efficiency is nonlinear. This finding suggests the existence of a limiting layer thickness beyond which additional material depth cannot be effectively compacted using the adopted roller parameters and number of passes.

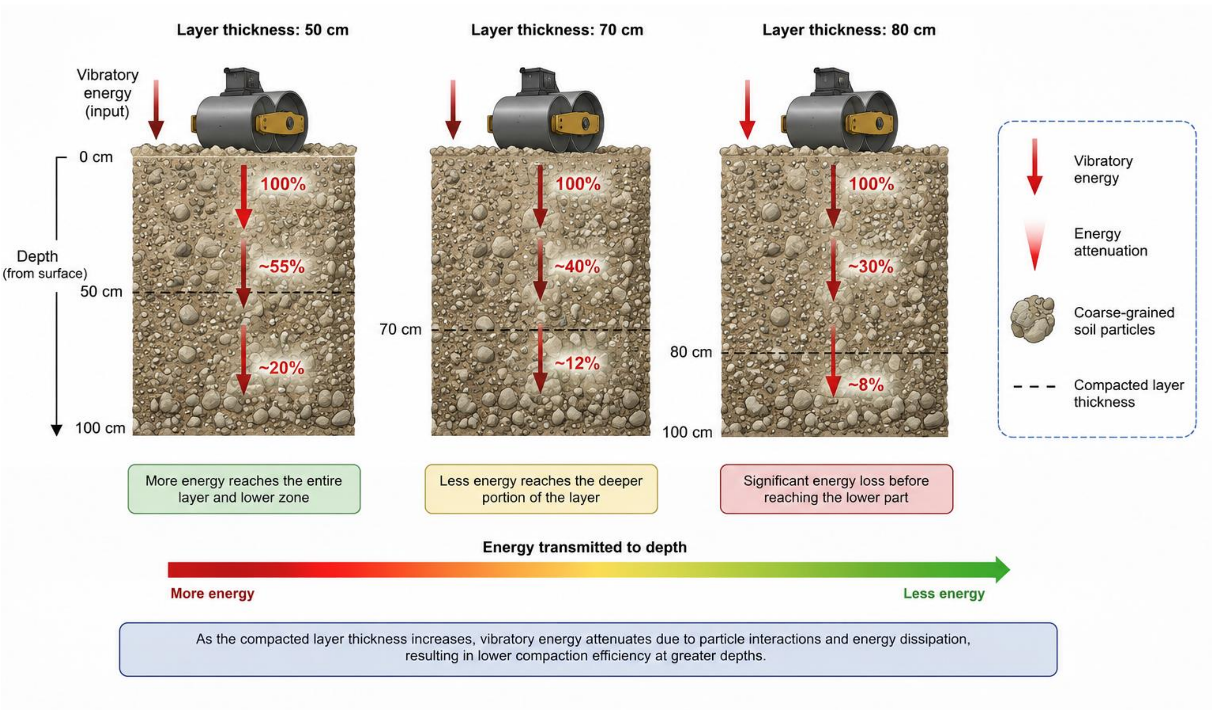


Fig. 6. Conceptual attenuation of vibratory energy in coarse-grained soil layers of different thicknesses.

The physical mechanism responsible for the observed reduction in dry density is schematically illustrated in Figure 6. The vibratory energy generated by the roller is transmitted from the surface into the underlying soil mass. During propagation, part of this energy is dissipated through interparticle friction, rearrangement of coarse particles, local particle rotation, and deformation at contact points. In a relatively thin layer, a sufficient proportion of the applied energy reaches the lower boundary of the compacted zone. In thicker layers, however, progressive energy attenuation prevents the lower part of the layer from reaching the same degree of particle rearrangement and densification as the upper part. This mechanism explains the reduced average dry density measured for the 70 and 80 cm layers.

From an engineering perspective, these findings have important practical implications for the construction of earth dams. Increasing the thickness of the compacted layer does not necessarily improve construction efficiency, despite reducing the number of placed layers [36-38]. On the contrary, excessive layer thickness may compromise compaction quality and require either additional roller passes or a reduction in layer thickness to achieve the target dry density.

Based on the obtained results, a compacted layer thickness of 50-70 cm is considered the most appropriate when using a 27-ton SANY vibratory roller. This range provides an effective balance between compaction efficiency and construction productivity while ensuring that the required density and engineering performance of the embankment are achieved.

3.2. Effect of Fine Fraction Content on the Compaction Efficiency of Coarse-Grained Soils

The content of the fine fraction is one of the key factors governing the compaction efficiency of coarse-grained soils. Variations in the proportion of particles smaller than 5 mm directly affect particle packing density, void ratio, and the redistribution of contact stresses within the soil skeleton. Therefore, a series of laboratory tests was conducted on model mixtures with different fine fraction contents to investigate their influence on the maximum dry density of coarse-grained soils.

The experimental results demonstrated that increasing the fine fraction content within the investigated range led to a gradual increase in the achieved dry density of the model mixtures. The lowest density values were obtained for mixtures containing approximately 10% fine particles, whereas increasing the fine fraction to 18-25% promoted more efficient filling of the voids between coarse particles, resulting in the formation of a denser and more stable soil structure [39].

The obtained results are summarized in Table 2.

Table 2. Effect of fine fraction content on the maximum dry density of model mixtures.

Fine fraction content (<5 mm), %	Maximum dry density of the model mixture, t/m³	Maximum dry density of natural soil, t/m³
10	1,88	2,00
18	1,98	2,13
25	2,06	2,25

The data presented in Table 2 indicate that increasing the proportion of fine particles promotes a more efficient packing of soil particles of different sizes. The fine fraction fills the voids between coarse particles, thereby reducing the void ratio and increasing the overall packing density of the soil. This mechanism contributes to the formation of a denser soil skeleton, resulting in improved structural stability and enhanced mechanical properties of the compacted material.

It should be noted, however, that the beneficial effect of the fine fraction is observed only within a certain range of its content. Once the optimum fine fraction content is reached, most of the voids between coarse particles become effectively filled. A further increase in the proportion of fine particles may lead to the formation of an excessive fine-grained matrix, reducing the direct contact area between coarse aggregates and impairing the drainage characteristics of the soil. Consequently, the dry density no longer increases and, under certain conditions, may even decrease [40-41].

Fig. 7 illustrates the relationship between the maximum dry density and the fine fraction content of the coarse-grained soil.

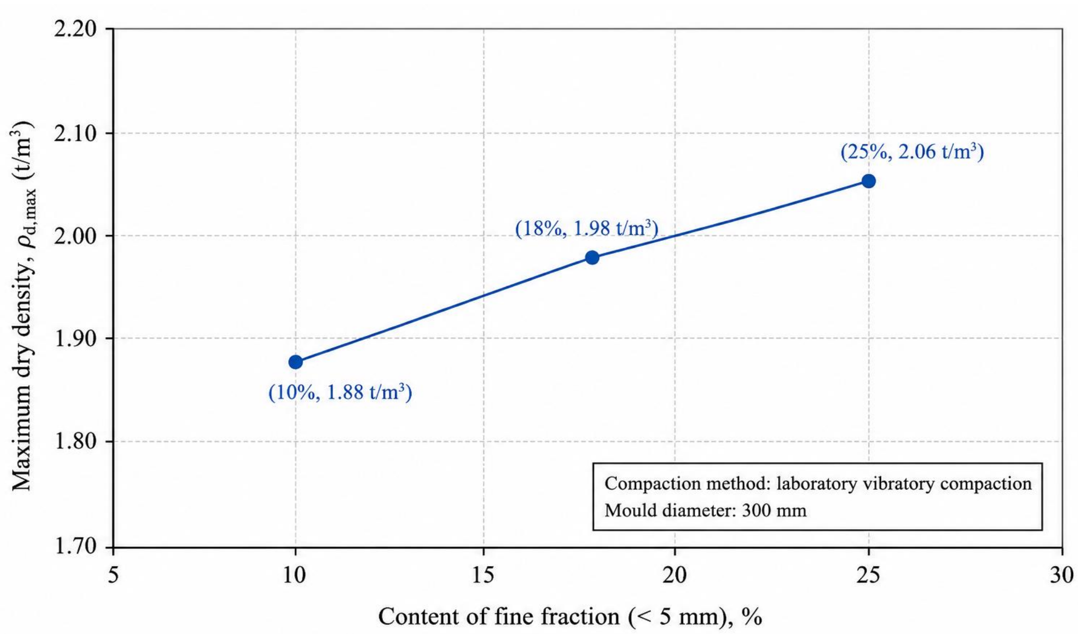


Fig. 7. Effect of fine fraction content on the maximum dry density of coarse-grained soil.

The obtained relationship exhibits a pronounced nonlinear trend. At the initial stage, an increase in the fine fraction content is accompanied by a substantial rise in the maximum dry density, which can be attributed to the effective filling of the voids between coarse particles. As the grain-size distribution approaches its optimum configuration, the rate of density increase gradually decreases because the soil structure reaches its maximum packing efficiency. This optimized particle arrangement provides the most favorable conditions for vibratory compaction, resulting in the highest achievable dry density.

The experimental findings are consistent with the current understanding of the mechanical behaviour of coarse-grained soils. An optimum grain-size distribution increases the number of interparticle contacts, reduces the likelihood of localized deformation, and promotes a more uniform distribution of externally applied stresses throughout the soil mass. Furthermore, the increase in dry density enhances the deformation modulus, reduces soil compressibility, and minimizes the potential for differential settlement during the long-term service life of hydraulic earth structures [42] .

From a practical engineering perspective, the obtained results demonstrate that the fine fraction content should be regarded as one of the key technological parameters in the preparation of coarse-grained materials for earth dam construction. Careful control of the grain-size distribution during quarry production and embankment placement makes it possible to achieve the required compaction quality without a significant increase in the number of roller passes. Consequently, this approach improves construction efficiency, shortens the construction period, and reduces overall construction costs while maintaining the required engineering performance of the compacted embankment.

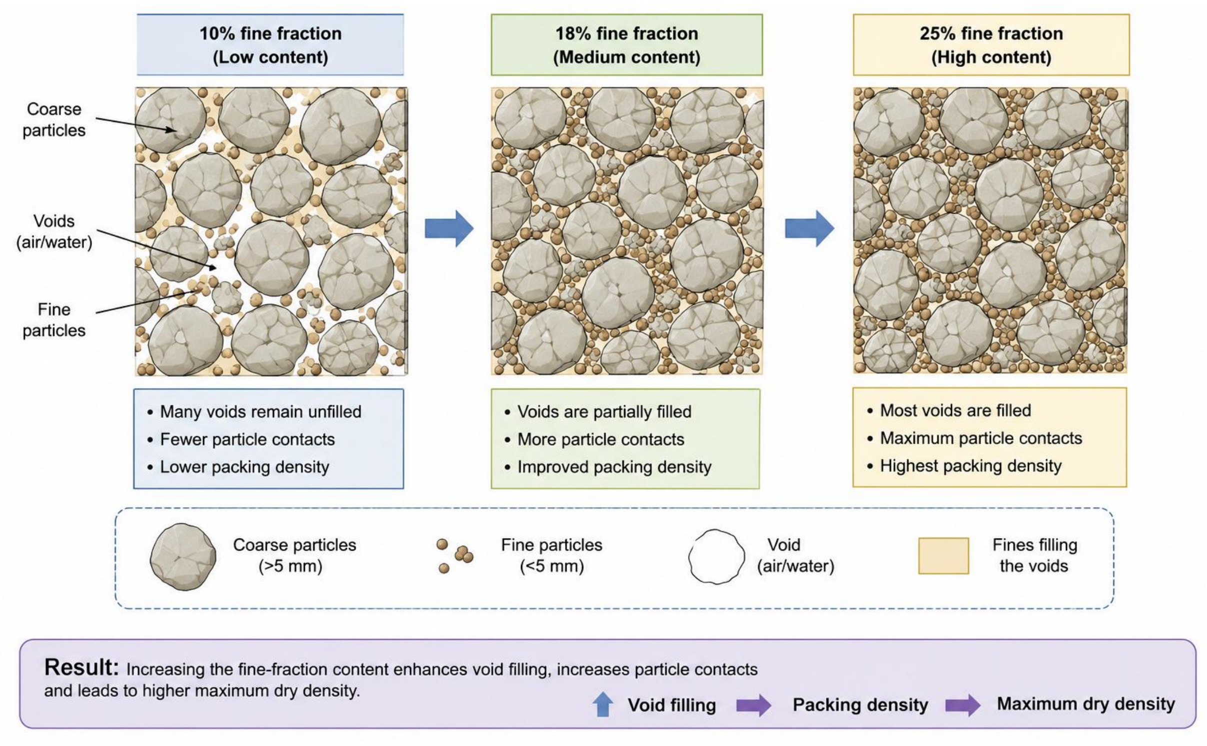


Fig. 8. Conceptual mechanism of void filling at different fine-fraction contents.

Fig. 8 schematically demonstrates the effect of fine particles on the internal packing structure of coarse-grained soil. At a fine-fraction content of approximately 10%, a considerable proportion of the voids between coarse particles remains unfilled. Increasing the fine fraction to 18% improves the filling of intergranular spaces and increases the number of particle contacts. At 25%, the soil skeleton develops a denser packing configuration, which corresponds to the highest maximum dry density recorded within the investigated range. The schematic interpretation is consistent with the experimental results and confirms that the fine fraction acts as an effective void-filling component.

3.3. Evaluation of the Grain-Size Modelling Method for Coarse-Grained Soils

One of the major challenges in the laboratory investigation of coarse-grained soils is the inability to directly test natural materials containing large rock fragments. In the investigated material, the maximum particle size reached 700-1000 mm**,** whereas the dimensions of conventional laboratory testing equipment impose strict limitations on the maximum allowable particle size. Consequently, direct testing of natural coarse-grained soils without prior modification cannot provide reliable estimates of their physical and mechanical properties.

To overcome this limitation, a grain-size modelling technique was adopted in the present study. The proposed approach preserves the proportion of the fine fraction while proportionally reducing the size of the coarse particles. Such a methodology ensures geometric similarity between the model mixture and the natural material, allowing the fundamental mechanisms of interparticle interaction and the overall grain-size distribution to be adequately reproduced under laboratory conditions.

During the preparation of the model mixtures, the intermediate grain-size distribution was determined using the following relationship:

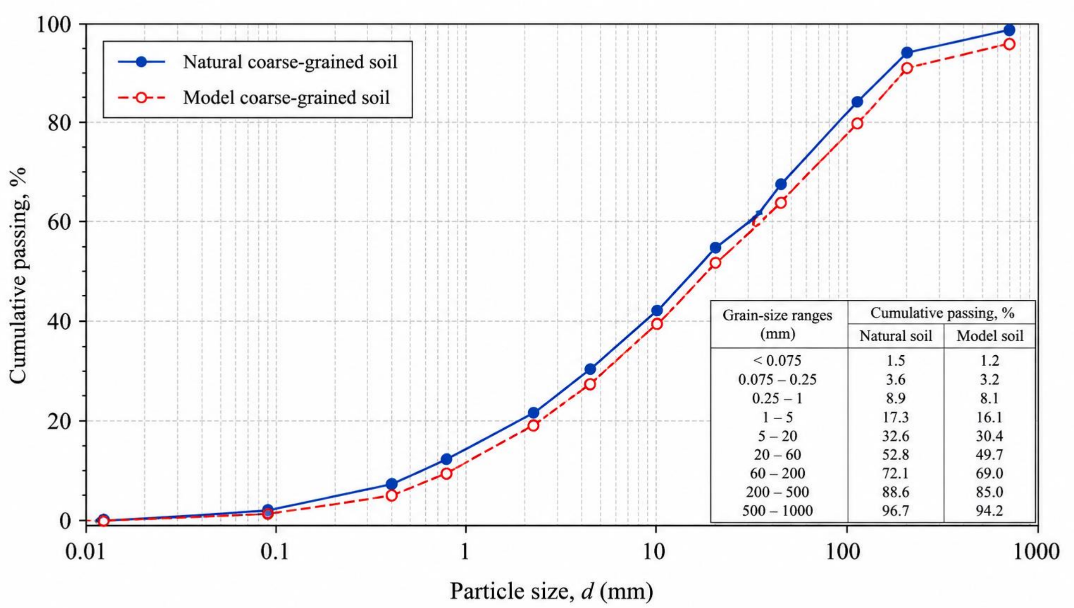
$$P_m = \frac{(100 - P_{<5}) \cdot P_n}{100} + P_{<5} \quad (2)$$

where:

- P_m – is the percentage of a given particle-size fraction in the model mixture (%);
- P_n – is the percentage of the corresponding fraction in the natural coarse-grained soil (%);
- $P_{<5}$ – is the content of particles smaller than 5 mm (%).

The proposed relationship eliminated the need for subjective selection of intermediate particle-size fractions and provided a unified procedure for constructing the grain-size distribution of the model mixtures. Unlike conventional approaches, which rely on arbitrary redistribution of individual particle-size fractions, the proposed method preserves the overall shape of the grain-size distribution curve of the natural coarse-grained soil. As a result, the model mixtures more accurately reproduce the structural characteristics of the original material and provide a reliable basis for laboratory investigations [43].

Fig. 9 compares the grain-size distribution curves of the natural coarse-grained soil and the developed model mixture.



Grain-size ranges (mm)	Cumulative passing, %	
	Natural soil	Model soil
< 0.075	1.5	1.2
0.075 – 0.25	3.6	3.2
0.25 – 1	8.9	8.1
1 – 5	17.3	16.1
5 – 20	32.6	30.4
20 – 60	52.8	49.7
60 – 200	72.1	69.0
200 – 500	88.6	85.0
500 – 1000	96.7	94.2

Fig. 9. Grain-size distribution comparison between natural coarse-grained soil and its laboratory model mixture.

Analysis of the obtained relationships shows that the overall pattern of particle-size distribution is preserved after the modelling procedure. Minor deviations are observed only in the range of the coarsest fractions, which is primarily associated with the dimensional limitations of the laboratory equipment and does not significantly affect the formation of the contact structure of the soil skeleton.

It is particularly important that the grain-size distribution curves coincide in the fine and medium fraction ranges. This ensures nearly identical conditions for the formation of the soil skeleton under both laboratory and field conditions. These particle-size ranges largely control void filling, particle packing density, and the efficiency of compaction energy transmission during vibratory loading.

To quantitatively assess the effectiveness of the proposed modelling method, the laboratory and field test results were compared. The comparison showed that the differences between the achieved density values remained within acceptable engineering limits. This indicates the high reproducibility of the modelling results and confirms the applicability of the proposed method for designing compaction technologies for coarse-grained soils.

The obtained results demonstrate that the use of model mixtures can substantially reduce the scope of costly field tests without compromising the reliability of experimental data. At the same time, the method enables preliminary evaluation of different grain-size distribution options, selection of the most effective compaction regimes, and prediction of the achievable soil density at the laboratory testing stage.

Therefore, the proposed modelling method can be regarded not only as a procedure for preparing laboratory specimens, but also as an independent engineering tool that improves the reliability of design decisions in the construction of large earth-filled hydraulic structures.

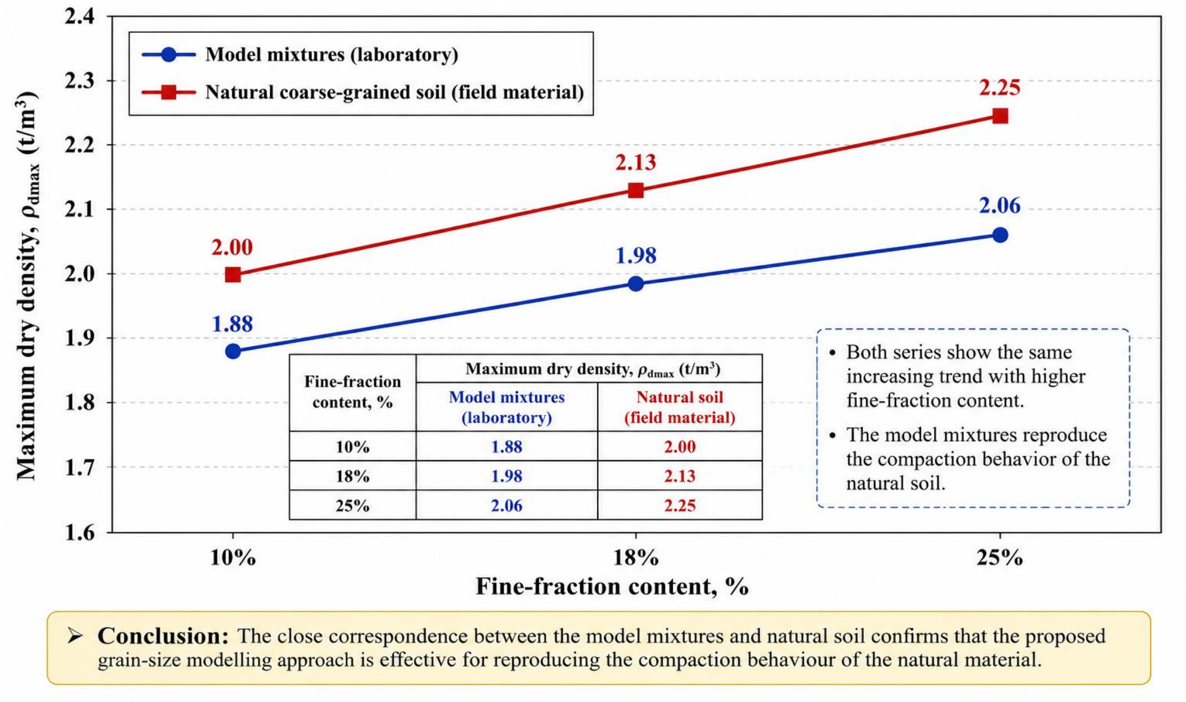


Fig. 10. Comparison of maximum dry density values obtained for the model mixtures and natural coarse-grained soil.

Fig. 10 compares the maximum dry density values of the laboratory model mixtures with those of the corresponding natural coarse-grained soil. Both datasets demonstrate the same increasing trend with increasing fine-fraction content. For fine-fraction contents of 10, 18, and 25%, the model-mixture densities were 1.88, 1.98, and 2.06 t/m³, respectively, whereas the corresponding natural-soil values were 2.00, 2.13, and 2.25 t/m³. Although the absolute density values of the model mixtures were lower, the similarity in the direction and magnitude of the response confirms that the adopted grain-size modelling procedure reproduces the main compaction behaviour of the natural material.

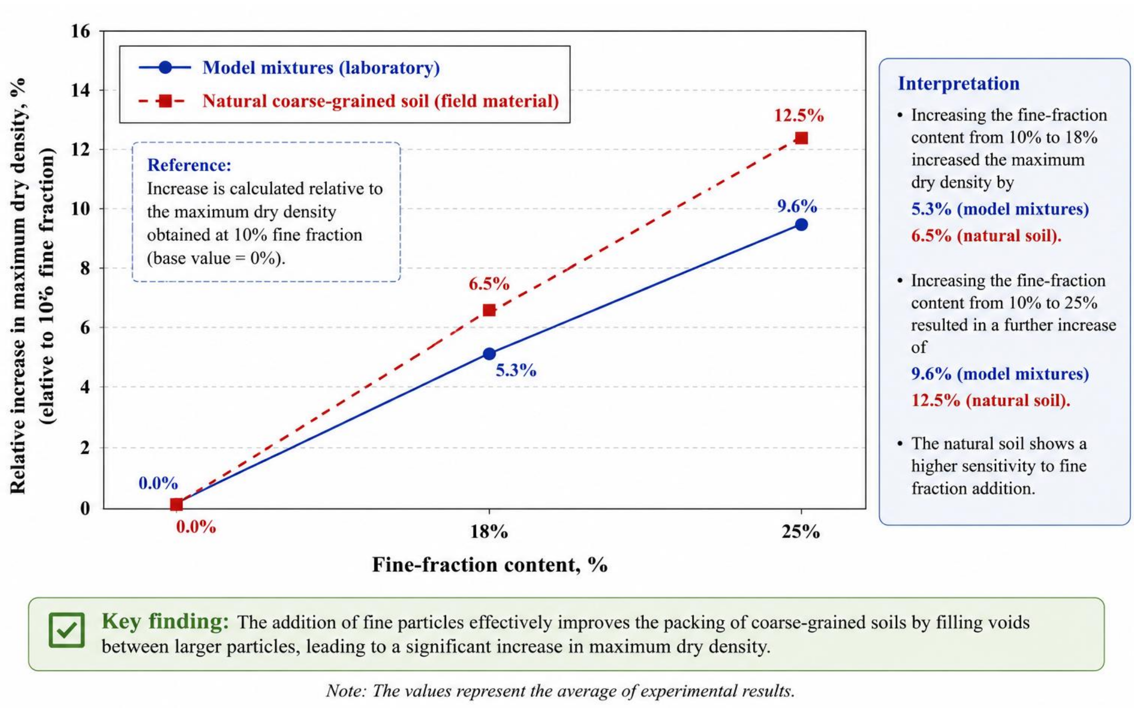


Fig. 11. Relative increase in maximum dry density with increasing fine-fraction content.

To compare the sensitivity of the two materials to changes in fine-fraction content, the density increase was normalized relative to the result obtained at 10% fines. Increasing the fine-fraction content from 10% to 18% increased the maximum dry density by approximately 5.3% for the model mixture and 6.5% for the natural soil. At 25% fines, the corresponding increases reached approximately 9.6% and 12.5%. The comparable response patterns indicate that the laboratory model adequately captures the effect of fine-particle addition, although the natural material exhibits a somewhat greater density gain.

3.4. Comparison of the Obtained Results with Recent Studies

The analysis of the laboratory and field investigations demonstrated that the compaction efficiency of coarse-grained soils is governed by the combined influence of grain-size distribution, fine fraction content, compacted layer thickness, and the operational parameters of the compaction equipment. The obtained results confirm that variations in each of these factors alter the interparticle contact network, void ratio, and the mechanism of dynamic energy transmission within the soil mass.

In recent years, considerable attention has been devoted to the compaction behaviour of coarse-grained soils. Most previous studies have focused on the individual effects of grain-size distribution, moisture content, compaction pressure, and vibration energy on the achieved soil density. However, the combined influence of these factors under both laboratory and field conditions has received considerably less attention.

The findings of the present study are consistent with the current understanding of the mechanisms governing the formation of dense coarse-grained soil structures. The results indicate that reducing the compacted layer thickness promotes a more uniform distribution of vibratory energy throughout the soil mass. Consequently, particle rearrangement becomes more effective, the void ratio decreases, and a higher dry density is achieved.

Particular attention should be paid to the role of the fine fraction. The experimental results demonstrate that fine particles act as a filler within the voids formed by coarse aggregates, thereby increasing the packing efficiency of the soil skeleton. Nevertheless, this beneficial effect is observed only up to an optimum fine fraction content. Beyond this optimum, an excessive amount of fine particles modifies the contact conditions between coarse particles, which may reduce drainage capacity and consequently decrease compaction efficiency[44].

These observations are in agreement with contemporary theories describing the contact mechanics of granular materials, according to which the maximum dry density is achieved when coarse and fine particles are combined in an optimum proportion. Under these conditions, a stable soil skeleton is formed, allowing external loads to be transmitted more uniformly through the particle contact network while minimizing the volume of internal voids.

It should also be emphasized that most previously published studies have been conducted either exclusively under laboratory conditions or solely through field investigations. In contrast, the present study proposes an integrated experimental approach combining laboratory and field testing through a unified grain-size modelling methodology. This approach ensures direct comparability of the obtained results and significantly improves the reliability and engineering applicability of the experimental findings.

An additional advantage of the proposed methodology is its ability to predict the achievable dry density during the laboratory stage of the investigation. This enables engineers to identify the optimum compaction parameters, determine the appropriate compacted layer thickness, and evaluate the influence of grain-size distribution before commencing large-scale field operations, thereby reducing the need for extensive and costly field testing.

From a practical perspective, the proposed approach can be applied in the development of construction specifications for earth dams, highway embankments, railway subgrades, and other geotechnical structures incorporating coarse-grained soils. Its implementation can improve compaction quality, reduce the occurrence of localized deformation, minimize additional construction work, and enhance the long-term reliability and service performance of earth structures.

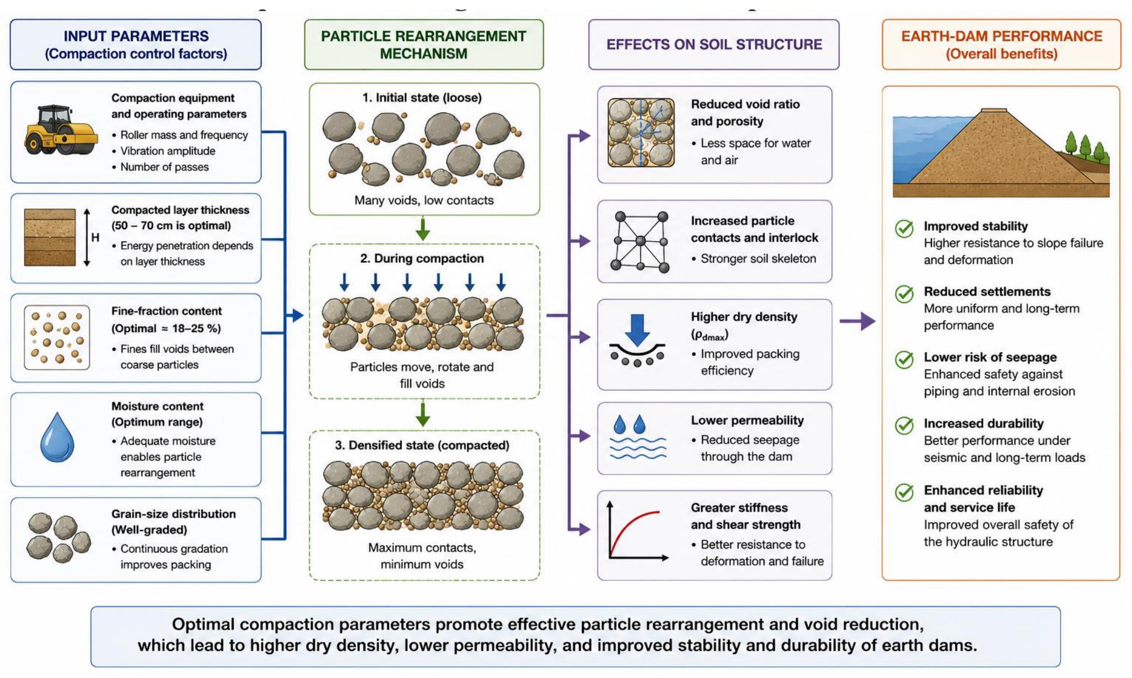


Fig. 12. Conceptual relationship between compaction parameters, particle rearrangement, and earth-dam performance.

The integrated mechanism established from the experimental programme is summarized in Figure 12. Appropriate selection of compacted layer thickness, fine-fraction content, moisture conditions, and roller operating parameters promotes more effective particle rearrangement. This process reduces the volume of internal voids and increases the dry density of the material. A denser and more uniform soil skeleton is expected to improve stiffness, reduce compressibility, limit differential settlement, and enhance the long-term performance of earth-filled hydraulic structures. Thus, the investigated parameters should not be considered independently, because their combined influence determines the final quality of the compacted embankment.

Overall, the results of this study demonstrate that the combined consideration of compacted layer thickness, grain-size distribution, and fine fraction content is essential for selecting rational compaction technologies for coarse-grained soils. Furthermore, the proposed grain-size modelling technique improves the reliability of laboratory investigations and provides a practical engineering tool for the design and construction of modern earth-filled hydraulic structures [45].

4. CONCLUSIONS

This study presents a comprehensive evaluation of the compaction performance of coarse-grained soils based on the combined analysis of laboratory and field investigations. The conducted experimental programme made it possible to establish the fundamental relationships governing the influence of grain-size distribution, fine fraction content, and compacted layer thickness on the achieved dry density of coarse-grained soils used in the construction of earth-filled hydraulic structures.

The results demonstrate that the compacted layer thickness is one of the key factors controlling the efficiency of vibratory compaction. The highest dry density was achieved at a compacted layer thickness of 50 cm**,** whereas increasing the layer thickness to 70 cm and 80 cm resulted in a progressive reduction in dry density due to the attenuation of vibratory energy transmission within the lower part of the soil mass. These findings highlight the importance of selecting an appropriate layer thickness to ensure effective compaction during the construction of large earth dams.

The study further confirms that the fine fraction content has a significant influence on the development of a dense and stable soil skeleton. An optimum grain-size distribution enables fine particles to effectively fill the voids between coarse aggregates, thereby increasing particle packing efficiency and improving the mechanical properties of the compacted material. However, excessive fine fraction content may alter the contact conditions between coarse particles, resulting in reduced compaction efficiency and deterioration of the drainage characteristics of the soil.

A grain-size modelling methodology for coarse-grained soils was developed and experimentally validated. The proposed approach, which preserves the proportion of the fine fraction while proportionally reducing the size of coarse particles, provides a high level of similarity between laboratory model mixtures and the natural material. Consequently, it improves the reproducibility of laboratory investigations and provides a reliable basis for selecting optimum compaction parameters.

The comparison of laboratory and field results confirmed the reliability of the proposed methodology and demonstrated its capability to predict the achievable dry density of coarse-grained soils at the laboratory stage of the investigation. This approach substantially reduces the need for expensive field testing, optimizes construction procedures, and improves quality control during compaction operations.

The practical significance of the present study lies in the applicability of the obtained results to the design and construction of earth-filled hydraulic structures, including earth-rockfill dams. The proposed recommendations can improve compaction efficiency, ensure the required dry density of embankment materials, reduce construction time, and enhance the long-term durability and operational reliability of hydraulic structures.

Overall, the findings of this study demonstrate that the combined consideration of compacted layer thickness, grain-size distribution, and fine fraction content is essential for the development of efficient compaction technologies for coarse-grained soils. Furthermore, the proposed grain-size modelling methodology represents a practical engineering tool that can be effectively applied in the design and construction of modern earth-filled hydraulic structures and provides a solid foundation for future research on the mechanical behaviour and compaction characteristics of coarse-grained geomaterials.

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