# Effect of Clods on the Permeability of Compacted Landfill Liners and Covers

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*Abstract:* Clayey soils in waste containment often form large clods, causing poor compaction, high inter-clod porosity, and greater water flow between clods. Consequently, for barrier liners and covers where permeability is the primary concern, any leakage resulting from poor compaction can lead to groundwater contamination. This paper presents the effect of the size of clods on the hydraulic conductivity of a marly soil with high plasticity used as a barrier to contain waste units. The hydraulic conductivity tests are conducted on samples with small and large clods compacted using the Standard Proctor Test.

*Key-Words:* - Landfill, compacted soil, permeability, soil clods, rigid-wall permeameter, liner performance, clayey soil.

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## 1 Introduction

Permeability of clayey soils is measured in the laboratory using rigid-wall or flexible-wall permeameters. However, field hydraulic conductivity often differs due to factors like scale effects, soil heterogeneity, sample disturbance, stress conditions, cracking, and fluid chemistry. While laboratory tests provide controlled baseline data, field results are typically higher and more variable, so reliable design requires conservative assumptions and in-situ verification.

Field-scale investigations further support these conclusions. [1], among others, demonstrated that the hydraulic conductivity increases systematically from laboratory permeameter tests to slug and pump tests, and ultimately to large-scale field pumping tests, indicating a clear upscaling trend.

Similarly, [2] analyzed 89 field tests on compacted clay liners and found that in-situ hydraulic conductivity is typically 10–100 times higher than lab values, with significant variability due to construction, scale, and environmental factors. Studies [3], [4], [5] also report field permeability exceeding laboratory results by more than an order of magnitude. The study, attributed the discrepancy to clod size differences between lab and field soils, but data were limited.

In this context, the present study investigates the influence of soil clods on the hydraulic conductivity of a compacted marl, contributing to improved understanding of one of the factors responsible for discrepancies between laboratory and field measurements.

## 2 Theory of clayey soil clods

[6] suggested that in compacted clays, flow occurs mainly through pores between clods rather than within them. Wet, soft clods deform more easily, so compaction above optimum water content reduces inter-clod voids and lowers hydraulic conductivity (Figure 1).

Consistent with this theory, [4], demonstrated that clod size and degree of breakdown critically control the permeability of compacted clay liners. Laboratory observations showed that dry-side compaction of large clods generates extensive inter-clod pores and markedly higher permeability, whereas wet-of-optimum compaction produces a more homogeneous structure with minimal inter-clod voids. Morphological analyses further confirmed that water flow in field liners occurs primarily through inter-clod macro-pores, with negligible flow through the clods themselves.

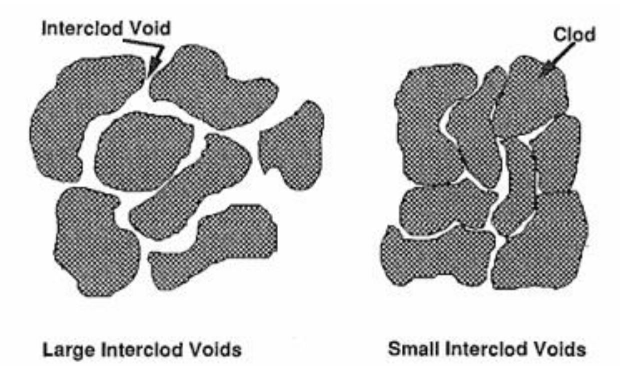


Fig. 1: Flow of water through relatively large pores between clods of soil, Source: [6].

# 3 Safety factor for hydraulic conductivity

The permeability is one of the soil properties most difficult to measure accurately. The difficulties encountered are largely due to the need to achieve a steady flow regime within the measuring cell and the required degree of saturation. As noted by [7], there is no international standard for permeability testing; consequently, the type of equipment and the testing procedure vary from one country to another, and even between laboratories within the same country.

For reasons of cost, laboratory tests are, in most cases, preferable to in-situ tests. However, laboratory testing should, as far as possible, reproduce actual field conditions.

In the case of permeability, additional reasons beyond economic considerations further justify the use of laboratory tests rather than in-situ measurements. These include the influence of water content, the ability to conduct comparative studies to evaluate the effects of different percolating fluids on permeability, and the practical difficulties associated with measuring permeability in-situ.

However, for saturated soils, in-situ permeability testing should be more representative than laboratory testing when it involves a large volume of soil, [8].

The factors contributing to discrepancies between laboratory and in-situ permeability measurements are numerous. The most frequently cited include difficulties in obtaining representative samples; larger clod sizes encountered in the field compared with those prepared in the laboratory; the use of high hydraulic gradients during laboratory testing, which may induce fine-particle migration and consequently reduce permeability; higher compaction water contents in laboratory specimens than those applied in the field; and the use of impact compaction methods in the laboratory that are not fully representative of field compaction practices. In addition, desiccation-induced cracks that develop in situ are generally absent from laboratory samples, and poor bonding between successive compacted soil layers in the field may further increase permeability (Figure 2). This latter issue can be mitigated by scarifying the soil and compacting it in a crosswise and alternating manner in both directions (Figure 3), [9].

Overall, among the various sources of error, the lack of representativeness of the tested sample relative to the in-situ soil mass appears to be the most difficult to eliminate.

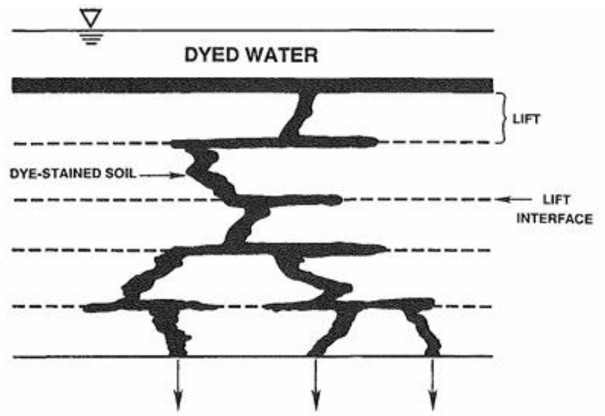


Fig. 2: Role of lift boundaries in connecting macrorolds in Successive Lifts, Source: [10].

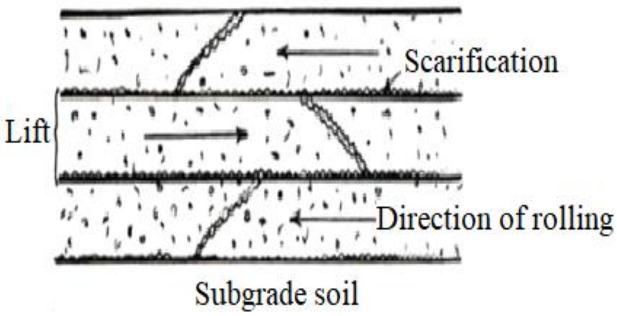


Fig. 3: Procedure for compacting the successive layers to mitigate the problem mentioned above, Source: [9].

It is therefore necessary to define a safety factor to account for field conditions that cannot be fully replicated in laboratory tests. The in-situ permeability can be estimated as:

$k_{in\text{-}situ} = F_s\, k_{laboratory}$

Where $F_s$ is the safety factor. This factor of safety allows a simple laboratory test to provide a recommended field permeability value.

However, defining a factor of safety for hydraulic conductivity is challenging. While standardized tests (e.g., for steel or concrete strength) allow for well-established safety factors, typically, 2.5–3.0

laboratory permeability tests lack standardization and are less reliable. Field permeability control is generally based on overall construction quality rather than individual measurements, which are often considered unrepresentative, [11], [12].
In conclusion, establishing a reliable safety factor for permeability requires both theoretical and experimental investigations.

# 4 Material and Methods

The study of the effect of clod size on permeability was carried out on a highly plastic marl classified as CH according to the Unified Soil Classification System (USCS). Some characteristics of this soil are presented in Table 1 and Figure 4.

Table 1. Characteristics of the marl, Source: Created by the author.

| | |
|---|---|
| Percent passing to: | |
| 80 µm | 100 |
| 2 µm | 60 |
| Liquid limit (%) | 63 |
| Plasticity index (%) | 41 |
| Specific area ($m^2/g$) | 84 |

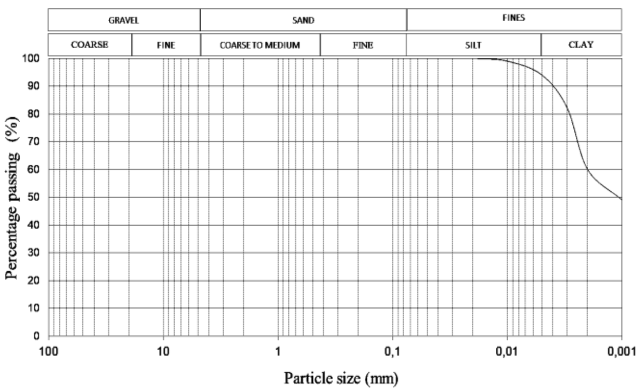


Fig. 4: Particle size distribution, *Source: Created by the author.*

After air-drying, the marl was crushed and separated into two clod-size fractions: large clods, consisting of soil particles passing through a 20 mm sieve and retained on a 5 mm sieve, and small clods, consisting of soil particles passing through a 5 mm sieve. The soil was then moistened to the desired water content and stored for at least 48 hours in airtight bags to promote uniform moisture distribution across the entire specimen.

The soil was compacted in a single lift using 25 blows directly in a 90 mm × 40 mm permeameter mold, following standard Proctor compaction energy.

Hydraulic conductivity was measured in a rigid-wall permeameter (Figure 5) under constant-head conditions. Tests were conducted until steady state was reached and lasted about two weeks. At the conclusion of testing, specimen saturation was 95–100%, confirming that the measured hydraulic conductivity values represent fully saturated soil conditions.

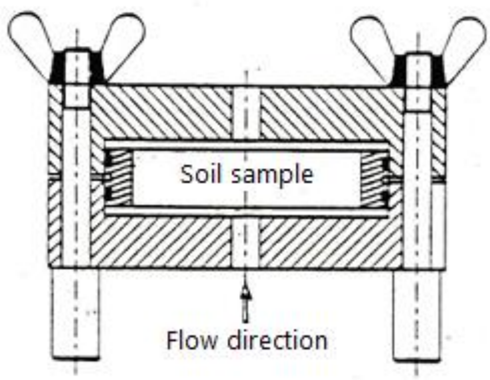


Fig. 5: Permeameter mold, Source: [9].

# 5 Results and Discussion

The test results (Figure 6 and Figure 7) indicate the following observations:

- Samples with small clods exhibit a flatter compaction curve than those with large clods, yet both clod sizes have nearly identical maximum dry unit weight and optimum water content.
- The maximum dry unit weight and optimum water content are $\gamma_{dmax}$ = 17 kN/m3 and $w_{opt}$ = 19.5% for soils with large clods, and $\gamma_{dmax}$ = 16.8 kN/m3 and $w_{opt}$ = 19% for soils with small clods, indicating only minor differences in compaction characteristics.
- On the dry side of the compaction curve, samples prepared with small clods achieve higher dry unit weights than those prepared with large clods. This behavior is consistent with findings reported by [3], for highly plastic clays.
- On the dry side, larger clods increase hydraulic conductivity, with differences widening at lower moisture due to inter-clod voids.
- When soils are compacted above the optimum moisture content, hydraulic conductivity is largely unaffected by clod size, since soft clods deform during compaction, reducing inter-clod voids and restricting water flow.

- For soils with small clods, minimum hydraulic conductivity is attained near the optimum water content, while for soils with larger clods it occurs at a water content about 2% higher. This difference reflects the greater moisture demand required to soften and compact larger clods.

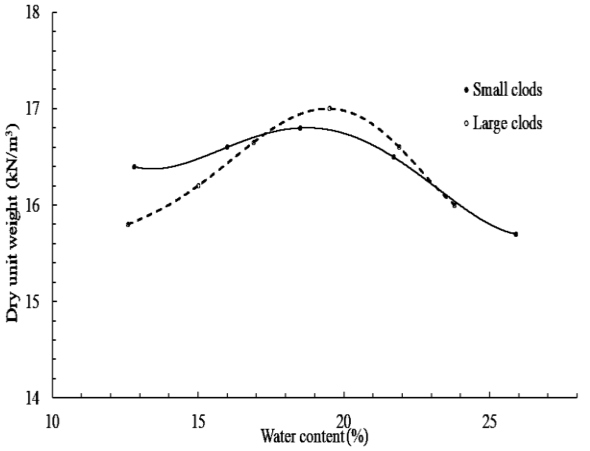


Fig. 6: Soil clod size effect on compaction curve, *Source: Created by the author.*

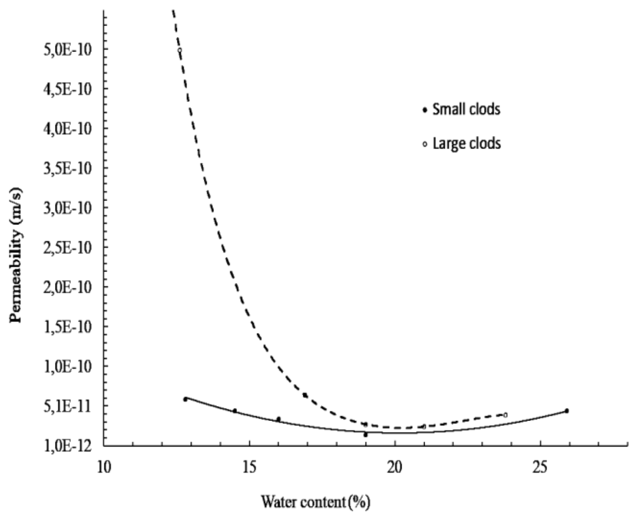


Fig. 7: Effect of clod size on the hydraulic conductivity, *Source: Created by the author.*

## 6 Conclusions

Clod size appears to be one of the principal factors contributing to the discrepancies commonly observed between laboratory-measured and in-situ hydraulic conductivity values.

To mitigate the effect of clod size on hydraulic conductivity, several measures may be adopted. First, the soil can be moistened to a water content that allows adequate deformation and remolding of clods during compaction, provided that this water content does not cause operational difficulties such as excessive rolling or instability under the compaction equipment. Second, the soil may be compacted at a lower water content; however, in this case, proper soil preparation prior to compaction is essential. This preparation involves breaking down large clods using sheepsfoot rollers, whose kneading action and high contact pressures are effective in destroying highly plastic clay clods and achieving uniform compaction, resulting in a more continuous particle-size distribution throughout the soil mass to be compacted.

Controlling clod size and compaction procedures promotes a more uniform degree of compaction and reduces inter-clod voids, leading to more homogeneous hydraulic conductivity and improved field performance of compacted clay barriers.

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### Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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### Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.