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RELIABILITY OF GUELPH PERMEAMETER FOR DETERMINING THE HYDRAULIC CONDUCTIVITY OF MINERAL LINERS

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ABSTRACT
The aim of this study is to evaluate whether the Guelph permeameter can be effectively used as a quick and reliable instrument to measure the hydraulic conductivity of compacted mineral liners. The investigation was carried out on two distinct areas of the final capping of a municipal solid waste landfill in Italy. On the first test site, hydraulic conductivity tests were performed using the Guelph permeameter, assessing reliability and repeatability of test results. On the second one, many undisturbed soil samples were taken and tested in the laboratory using a modified oedometric apparatus as a falling-head permeameter. Further hydraulic conductivity tests with Guelph permeameter were also performed in the holes made by soil sampling. The campaign was integrated with in situ density tests using the calibrated sand method, to check the uniformity of the compaction degree of liners. A final comparison between hydraulic conductivity obtained in situ and in the laboratory was proposed and critically analysed. The experiments performed on the two test sites with the Guelph permeameter and their statistical processing demonstrate that the instrument is not only economical and easy to use, but also reliable if used with appropriate precautions.

1. INTRODUCTION

The main environmental problems of a municipal solid waste (MSW) landfill are associated with the control of leachate and biogas emissions into the surrounding environment. Mineral liners are compacted at the bottom and top of landfills to achieve suitable hydraulic conductivities. National regulations generally establish the minimum thickness of liners and their maximum hydraulic conductivity k, according to the nature of waste stocked inside the landfill (European Council, 1999, 2018). No further details are generally provided on the experimental procedure to determine the coefficient k, which can be obtained, directly or indirectly, using either laboratory or field tests. The choice of a specific procedure depends on many variables, such as nature, water content and degree of saturation of soil, fluid permeant, required accuracy of instruments, available time and economical budget.

Many studies have shown that hydraulic conductivity can vary considerably depending on the applied experimental procedure (Fallico et al., 2006). Moreover, field measurements often provided values of k smaller than those obtained through laboratory procedures. This could be due to the presence of air trapped during wetting, which causes partial saturation of the soil, hence a lower permeability (Fodor et al., 2011; Jačka et al., 2014; Rezaei et al., 2016).

The Guelph, auger-hole, and falling-head permeameter methods in clay to sandy loam soils were compared by Gallichand (Gallichand et al., 1990). The results showed that the geometric mean of K from the Guelph was less than that obtained by the falling-head method. It was also found that Guelph permeameter measurements underestimated the K_s value compared to the laboratory falling-head method, with differences even exceeding an order of magnitude (Feki et al., 2020).

Similar results were also found in studies carried out in the agricultural sector. Soto & Kiang (Soto & Kiang, 2018) found that the hydraulic conductivities resulting from tests with a double ring infiltrometer are, on average, 2.2 times greater than those obtained with the Guelph permeameter. However, agricultural soils are characterized by hydraulic conductivities 2-3 orders of magnitude greater than those investigated in this paper.

In this paper hydraulic conductivity obtained with laboratory falling-head tests and with Guelph permeameter on two test sites are compared.

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2. PERMEABILITY TESTS

2.1 Field permeability test with Guelph permeameter

The Guelph permeameter allows the on-site determination of the hydraulic conductivity of soils. It is easy to transport, place and use, cheaper than other permeability tests, and can provide reliable data if properly used. Furthermore, it can measure the three-dimensional flow of the permeating liquid, resulting from the horizontal and vertical components. The Guelph (2800K1 model) permeameter was used in this study. To interpret the experimental results, the following equations were used (Elrick et al., 1989; Elrick & Reynolds, 1992; Reynolds et al., 1983, 1985; Reynolds, 1986; Reynolds & Elrick, 1985, 1987; Zhang et al., 1998). The lowering rate R of the reservoir water level is considered equal to:

$$R_i = \frac{H_i - H_{i-1}}{t_i - t_{i-1}} \quad \left[\frac{m}{s}\right] \tag{1}$$

where (Figure 1):
H are the initial and final hydraulic heads in a specific time interval (m);
t is the cumulative reading time (s);
i is the number of measurements,
and its mean (R) is:

$$\bar{R} = \frac{1}{I} \cdot \sum_{i=1}^{I} R_i \quad \left[\frac{m}{s}\right] \tag{2}$$

where I is the total number of measurements.

The first R values are generally neglected as water flow has not yet stabilized. Flow rate (Q) can be expressed by the following equation:

$$Q = A \cdot \bar{R} \qquad \left[\frac{m^3}{s}\right] \tag{3}$$

where A is the cross-sectional area of the tank, equal to 216 mm^2, when only the internal tank is used, and to 3522 mm^2, when both tanks are used. Finally, hydraulic conductivity (K_{fs}) is calculated as follows:

$$K_{fs} = \frac{C \cdot Q}{2 \cdot \pi \cdot H^2 + \pi \cdot a^2 \cdot C + 2 \cdot \pi \cdot \frac{H}{\alpha^*}} \tag{4}$$

where:
C: dimensionless shape factor,
Q: water flow rate (m^3/s),
H: water height in well (m),
a: well radius (m),
α*: macroscopic capillary length (m^{-1}).
α* and C are calculated using Table 1.

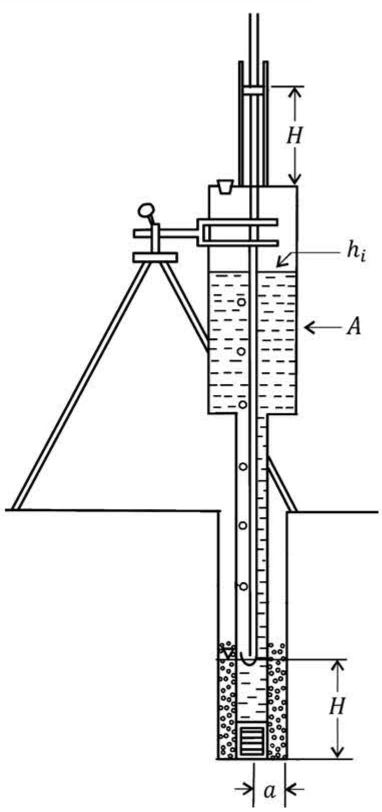

FIGURE 1: Working section of the Guelph permeameter.

The Guelph permeameter is essentially a Mariotte bottle and allows you to maintain a constant head within a small cylindrical well dug into the ground with special tools. Water seeps into the soil through the wet bottom and sidewalls and is replaced by new water flowing from the Guelph permeameter to maintain the level in the sump. By measuring the water level in the Guelph permeameter tank in two successive instants, measurement of the water infiltrated in a specific time can be obtained. From these measurements it is possible to obtain an estimate of the hydraulic conductivity at field saturation (K_{fs}), which is a fundamental parameter for modelling the water seepage through soils (Bagarello & Iovino, 2010).

Particular attention should be paid to the following aspects:

- Field saturated hydraulic conductivity (K_{fs}) - Compacted mineral liners always have a degree of saturation less

TABLE 1: Soil categories with respective α* and C (Reynolds et al., 2008).

Soil category	α* (m^{-1})	C
Compacted, structureless, clayey, or silty materials such as landfill caps and liners, lacustrine, or marine sediments, etc.	1	$\left(\frac{H/a}{2.081 + 0.121\,(H/a)}\right)^{0.672}$
Porous materials that are both fine textured and massive. Unstructured clayey and silty soils, as well as fine structureless sandy materials may be included	4	$\left(\frac{H/a}{1.992 + 0.091\,(H/a)}\right)^{0.683}$
Most structured and medium textured materials. Structured clayey and loamy soils, as well as unstructured medium sands may be included. This category is generally the most appropriate for agricultural soils	12	$\left(\frac{H/a}{2.074 + 0.093\,(H/a)}\right)^{0.754}$
Coarse and gravelly sands. Highly structured soils with large and numerous cracks and macropores may also be included	36	

than 100% and this strongly influences the infiltration process (Reynolds et al., 1983). For this reason, K_{fs} is used in equation (4) in substitution of fully saturated hydraulic conductivity (K_s), used only in laboratory tests.

- Macroscopic capillary length (α*) - This parameter, tabulated and dependent only on soil nature, is more reliable in partially saturated soils. However, K_{fs} does not strongly depend on α*, particularly for high H/a ratio (Elrick et al., 1989).
- Shape factor (C) - This factor which is also tabulated, derives from numerical analysis and depends mainly on the H/a ratio and soil structure (α*). Estimation of C factor becomes less reliable if the soil is close to saturation. However, for most applications, the tabulated values may be considered reliable (Reynolds & Elrick, 1987).

To obtain valid experimental results, some practical precautions must be taken as follows:

- Point measurements - The test aims to evaluate the punctual hydraulic conductivity of a compacted mineral liner. Cracks or preferential paths may be present in sampled soil, where hydraulic conductivity is much higher. Therefore, a statistically significant number of measurements must be made to correctly assess hydraulic conductivity.
- Soil homogeneity - All formulas assume a homogeneous, isotropic and uniformly wetted soil. If the test is carried out on heterogeneous soils, the estimation of α* is difficult and hydraulic conductivity could give unlikely results (Reynolds, 1986). Therefore, when analysing a stratified soil with different permeabilities, it is recommended to carry out many tests at different depths corresponding to the soil stratification (Xiang et al., 1997).
- Achievement of steady state condition - In very permeable soils the steady state condition is achieved quite quickly (order of minutes), while a longer period (order of hours) could be required in poorly permeable soils. Therefore, the test duration should be adapted to the nature of the investigated soil.
- Gravity influence - Gravity can affect the experimental results. However, the amount of flow that can be attributed to gravity decreases rapidly as the H/a ratio increases; for H/a ≥ 5 the gravitational flow can be neglected, having an influence less than <5% (Reynolds et al., 1983).
- Hole smearing - During the excavation a thin smeared layer can be generated along the lateral surface of the hole, especially with fine-grained soil having higher water content. An underestimation of permeability, due to the pore closure around the test hole, could be obtained (Reynolds, 1986). To limit smearing, a sharp auger should be used, making a gentle downward pressure, and the hole surface can be scrubbed with a brush or small sprocket (Reynolds, 1986). The infiltration rate values in smeared wells could be less than half of those not smeared (Koppi & Geering, 1986).
- Well collapse - Test wells could collapse during the excavation or during the test in granular soils. This problem can be overcome by using a pointed casing (Reynolds & Lewis, 2012).
- Temperature changes - Heating of water inside the tank, due to direct solar radiation, can prevent air from rising due to its thermal expansion. Furthermore, hydraulic conductivity is inversely proportional to water viscosity, which is inversely proportional to its temperature. Therefore, K_{fs} will increase with the water temperature: an increase of 15°C can lead to an increase in measured permeability up to 45% (Reynolds & Topp, 2008).

2.2 Falling head permeability test in a modified oedometric cell

Falling-head permeability test in an oedometric cell is suitable for low permeability soils, since the test duration is short and even small flow rates can be easily measured using a graduated burette. The test follows the ISO 17892-11 procedure and is carried out using an oedometric apparatus, modified for permeability tests (ISO 17892-11:2019, 2019). Each sample is previously saturated and consolidated with a set of increasing vertical pressures. The hydraulic conductivity of a saturated soil sample (K_s) can be calculated as follows:

$$K_s = \frac{a \cdot L}{A \cdot (t_2 - t_1)} \cdot \ln\frac{h_1}{h_2} \qquad \left[\frac{m}{s}\right] \tag{5}$$

where:
A: burette area (m^2);
L: sample height (m);
A: cross-sectional area of sample (m^2)
h_1 and h_2: initial and final water level (m);
t_1 and t_2: initial and final testing time (s).

2.3 Planning of the tests

The on-site experimentation was carried out in a municipal solid waste (MSW) landfill, located at Grumolo delle Abbadesse in the north-eastern part of Italy. The landfill area covers approximately 160,000 m^2 and has a total capacity of 1,125,000 tons of MSW. Compacted mineral barrier and rainwater drainage of the landfill cover were made using silty clay and silty sand respectively, coming from local excavations. Furthermore, the biogas drainage layer was made with selected inert waste, able to perform the required function of a gravelly layer. The liquid limit (w_L) and the plasticity index (PI) of the silty clay used in the compacted barrier were between 44-46% and 19-22%, respectively.

Two different areas were selected on the temporary cover of the landfill (Figure 2) to test the Guelph permeameter. Clayey soil was spread over the test area in layers 0.40 m thick, and compacted with four passes of a dumper loaded with 45 tons of sand, obtaining a degree of compaction around 95 % of standard Proctor dry density (corresponding to a compaction energy of 593 kJ/m^3). Although the dumper is not a vehicle specifically designed for compaction, it was demonstrated that it is suitable for this purpose (Moraci et al., 2018).

2.3.1 First test field

The first test field aimed to evaluate reliability and repeatability of the experimental results. A rectangular area

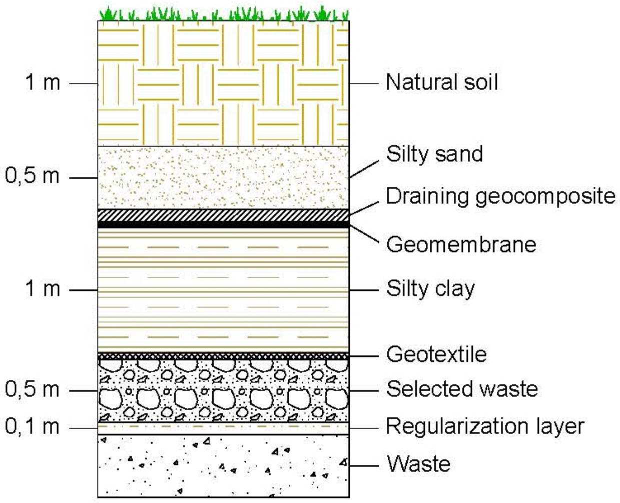

FIGURE 2: Section of the final cover in the Grumolo delle Abbadesse landfill.

of 9.0 m x 4.0 m of mineral liner was selected (Figure 3). Clayey soils were spread and compacted obtaining a final layer 2 m thick. Before test execution, the shallowest layer, 0.3 m thick, was removed. Twenty-four hydraulic conductivity tests were performed using the Guelph permeameter. In most tests, an interval t of 2 minutes between readings was enough to achieve a constant lowering rate. However, in case of clay lenses, the interval was increased to 5 minutes to achieve a higher difference between consecutive readings. In most tests, both tanks (total area A = 3522 mm^2) of the permeameter were used. When clay lenses were met, only the internal tank was used (A = 216 mm^2) to get adequate resolution when taking a reading. Three different test pit depths were chosen: 0.2 m (A), 0.3 m (B) and 0.5 m (C). It was thus possible to obtain results that were more representative of the entire layer, characterizing possible soil inhomogeneity. A tripod was used to minimize the permeameter settlement, sometimes digging to position the legs correctly. The well was dug with the augers supplied in the kit, so its radius was always equal to 30 mm.

A hydraulic head in the well H = 0.15 m was chosen, suitable for moderately permeable soils, from silty sands to silty clays (Elrick et al., 1989). The macroscopic capillary length α^* = 1 m^{-1} and the shape factor C were defined using Table 1. In general, the volume tested roughly corresponds to the size of the wetted zone around the test well. In moderately permeable soil, this corresponds to a spheroid extending from 0.1 m to 0.2 m outward from the submerged surface of the test hole (Elrick et al., 1989). Therefore, a spacing of 1 m among the holes was chosen (Figure 3). A hydraulic head of 0.15 m was assumed (Figure 4).

2.3.2 Second test field

The second test field was designed to evaluate the difference between the results of the two types of permeability tests, after having characterized the investigated soil. A rectangular area of 9.5m x 4m was prepared using the same soil of the previous testing area (Figure 5). In this case soil was selected before laying, to isolate the most homogeneous fraction possible. The final thickness was greater than 1 m, also considering the effects of compression and swelling. Again, the first 0.3 m of soil was removed just before starting each test. For the laboratory analyses, twelve cylindrical samples of 80 mm in diameter and 300 mm in length were taken. For comparing in situ and in laboratory permeability, twelve hydraulic conductiv-

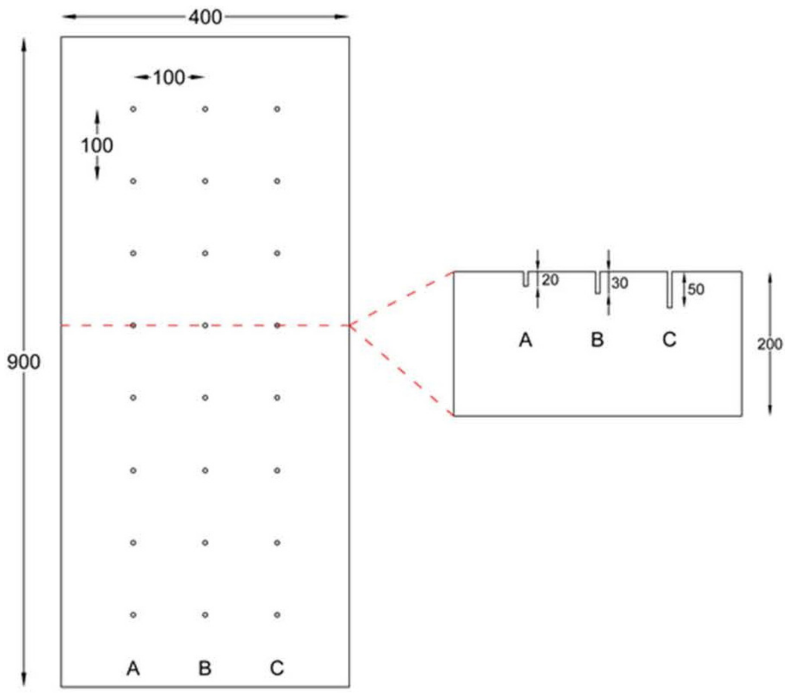

FIGURE 3: Plan and section of the first test site (measurements expressed in cm).

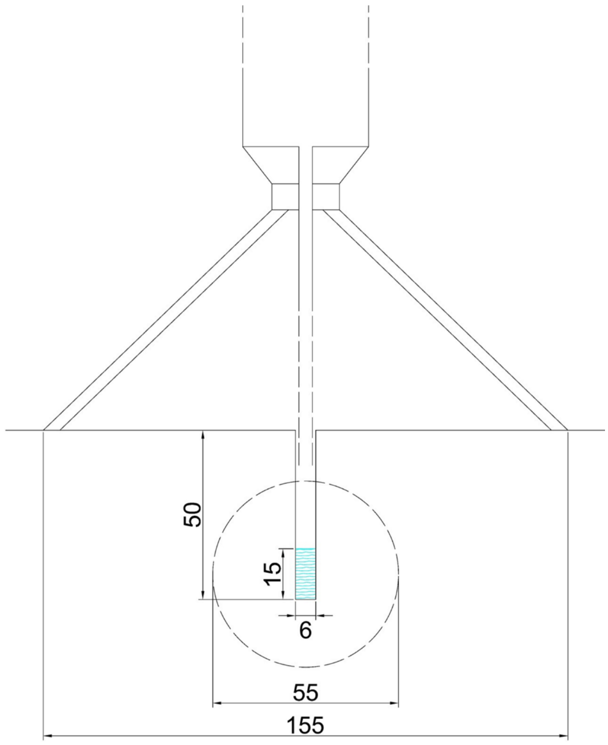

FIGURE 4: Wet zone and tripod foot around the test hole (measurements expressed in cm).

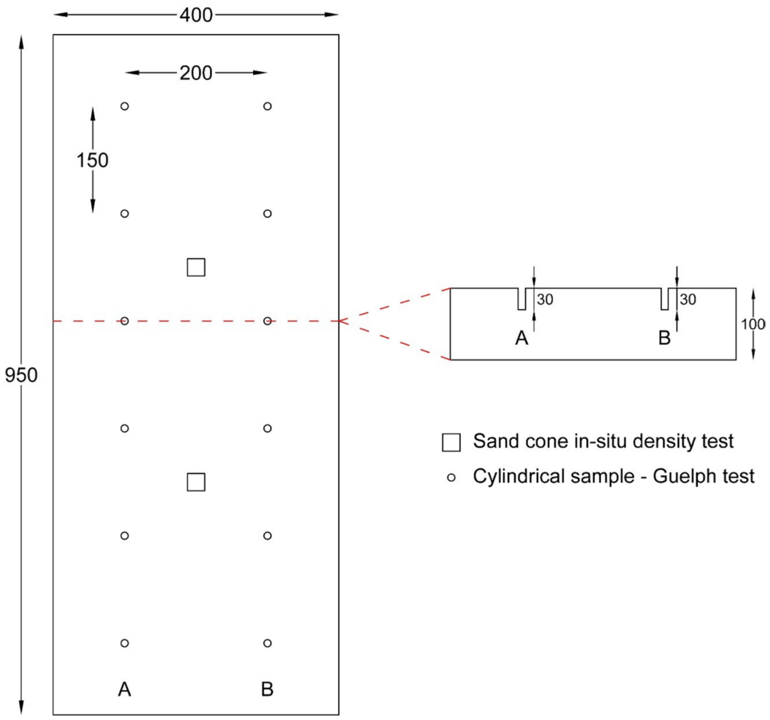

FIGURE 5: Plan and section of the second test site (measurements expressed in cm).

ity tests with Guelph permeameter were performed in the holes where sampling was made. In almost all tests, only the internal reservoir (A = 216 mm^2) was used, with a time interval between readings of five minutes. Only in the case of sand lenses was it necessary to use both tanks (A = 3522 mm^2) and a time interval of two minutes, to obtain a clear difference between consecutive measurements. Well sizes were determined by the envelope for the laboratory sampling (80 mm in diameter and 300 mm in height), then the radius a of the well equal to 40 mm. To maintain the ratio $H/a \geq 5$ and to avoid the influence of gravity, a hydraulic head H = 0.23 m was chosen. As for the first test field, the macroscopic capillary length $\alpha^* = 1\ m^{-1}$ and the form factor C were defined by means of Table 1.

Tests were preceded by two in situ density tests with a sand volumenometer. Laboratory analyses included, for each sample, the soil classification by particle size distribution and sedimentation: twelve sieves with descending diameters from 100 to 0.063 mm were used and then the remaining soil was suspended in an ASTM 152H hydrometer with distilled water and sodium hexametaphosphate ($Na_6P_6O_{18}$) at a controlled temperature of 20°C. Then twelve falling head hydraulic conductivity tests were performed in a modified oedometric cell: from the lowest part of each cylindrical sample a disk of 4000 mm^2 in area and 20 mm in height was obtained. Each sample was consolidated at 25 kPa and several falling head hydraulic conductivity test cycles were carried out until the system stabilized. The area a of the burette was equal to 19.6 mm^2. The test was performed at 20°C. The initial water level in the burette was h_1 = 1 m. To minimize the inevitable heterogeneity of the investigated soil, the area of both test fields was reduced to the minimum possible size, considering the radius of influence of the wet ground around the holes and the minimum space required for the deployment of the tripod.

2.4 Test results

The processing is based on the following statistical indicators:

arithmetic mean $$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \quad (6)$$

median $$Med(x) = \frac{x\left(\frac{n}{2}\right) + x\left(\left(\frac{n}{2}+1\right)\right)}{2} \quad (7)$$

standard deviation $$\sigma = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (8)$$

variance $$\sigma^2 = \frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2 \quad (9)$$

coefficient of variation C_v $$C_v = \frac{\sigma}{\bar{x}} \quad (10)$$

where
n is number of data.

In addition, the Bland-Altman plot was used to statistically assess the agreement between Guelph permeameter results and laboratory data (Braždžionytė & Macas, 2006; Ghosh et al., 2019). In the Bland-Altman plot, the mean of two groups of data is plotted on the x axis and the difference between them on the y axis. The mean of the difference between the two methods is defined as bias. The 95 % upper and lower limits of agreement are equal to ±1.96 times the standard deviation of the difference.

2.4.1 Results of hydraulic conductivity tests with Guelph permeameter on the first test field

On the first test field soil was quite heterogeneous, with frequent sand and clay lenses (Figure 6). For this reason, the measured hydraulic conductivity varied in the area, also in samples located at the same depth (Figure 7). The maximum permeability ($k = 1 \cdot 10^{-8}$ m/s), required by many national regulations, was exceeded in most cases. Two of the twenty-four tests were invalidated by the sinking of the permeameter in the well. The average permeability on

TABLE 2: Statistical parameter of Guelph tests on the first test site.

	k_{fs} (m/s)
$\bar{x}$ (m/s)	3.8E-07
median (m/s)	2.2E-07
σ (m/s)	6.4E-07
σ^2 $(m/s)^2$	4.0E-13
C_v	1.68

site k_{fs} was $3.8 \cdot 10^{-7}$ m/s and the median was $2.2 \cdot 10^{-7}$ m/s, compatible with a loamy soil, while standard deviation and coefficient of variation showed high values (Table 2).

In conclusion, despite the high soil heterogeneity, the preliminary study was successfully completed, since the results are reliable and reproducible, with consistency across the data.

2.4.2 Results of hydraulic conductivity tests with Guelph permeameter on the second test field

The grain size distribution curves of soils are reported in Figure 8. They are quite homogeneous and can be classi-

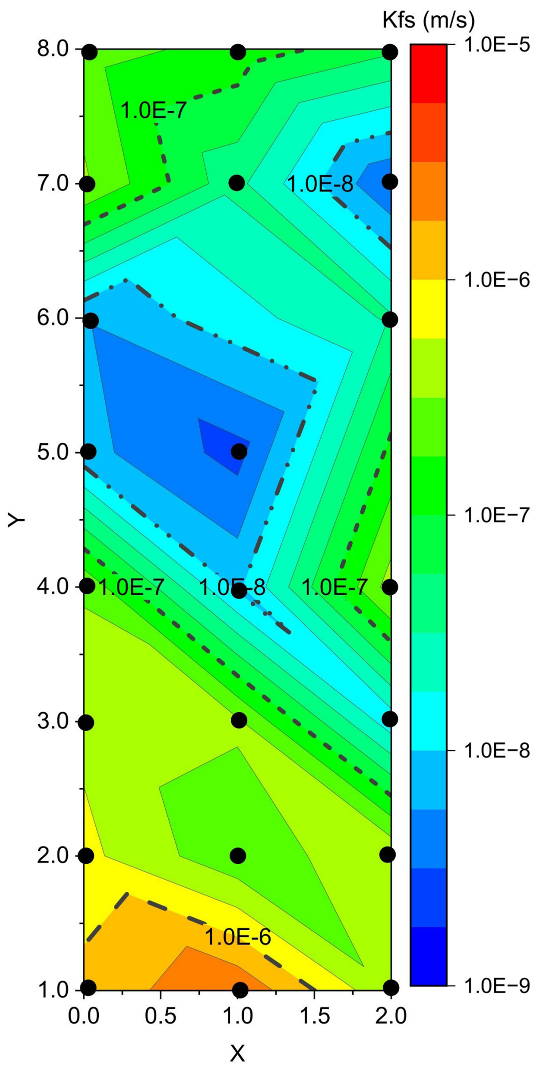

FIGURE 6: Distribution of the hydraulic conductivity determined with Guelph tests on the first test site.

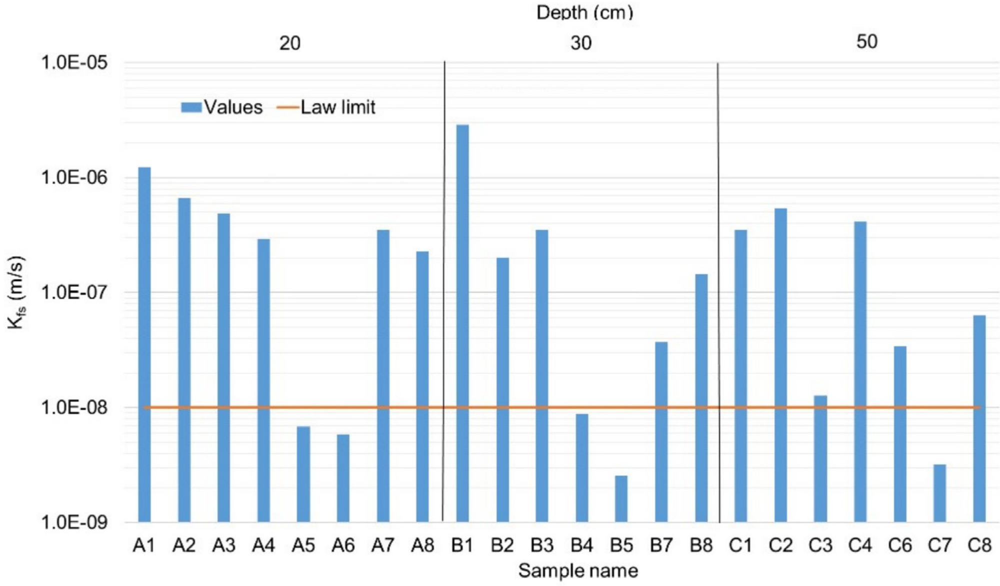

FIGURE 7: Hydraulic conductivity determined with the Guelph tests on the first test site.

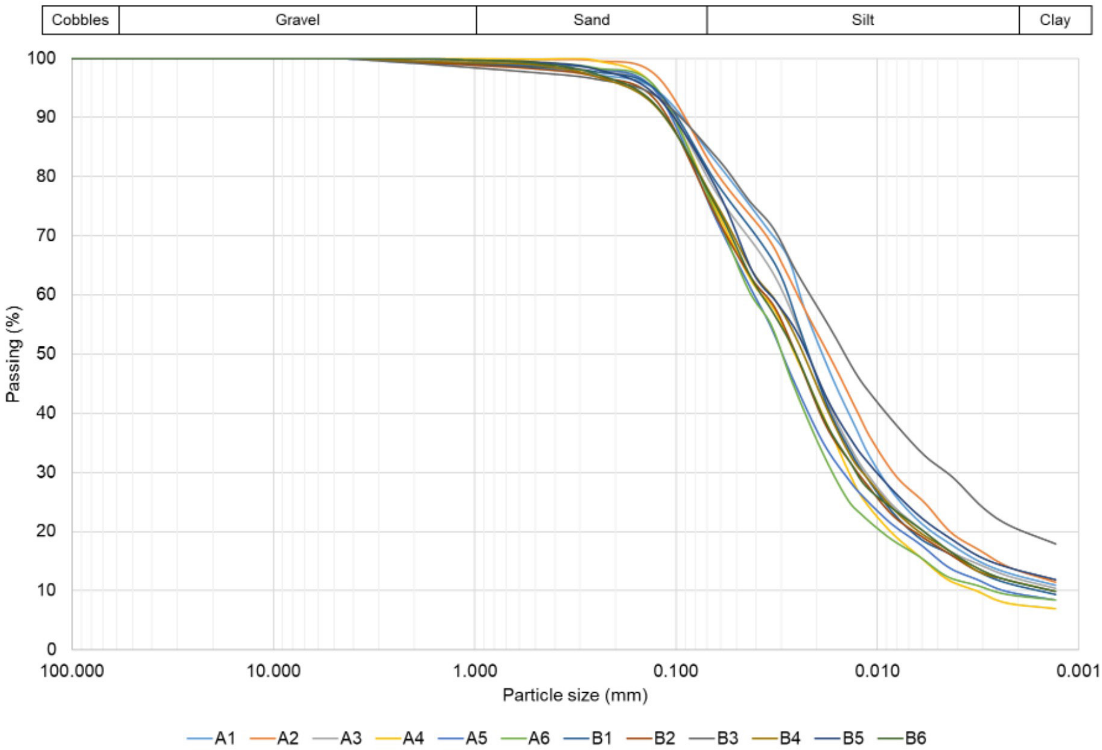

FIGURE 8: Grain size distribution of the investigated soil samples.

fied as silt (65.2%) with a small percentage of sand (22.7%) and clay (11.8%) (Table 3). Values of density obtained on site were very similar to those determined in the laboratory.

On the second test field, the results of the permeability tests both in the laboratory and on site were less dispersed (Figure 9 and Figure 10). The maximum coefficient of permeability, required by most European regulations, was respected in most samples. Two of the twelve tests were neglected due to instrument errors. The mean and the median on-site hydraulic conductivity were lower than those on the previous test site (1.1×10^{-8} m/s and 5.3×10^{-9} m/s) by one order of magnitude. The corresponding laboratory samples reported a slightly higher mean value (1.2×10^{-8} m/s and 9.1×10^{-9}) (Table 4).

Figure 11 shows the hydraulic conductivity values vs the clay percentage: the higher the clay content, the lower the permeability. No noticeable trend in permeability was detected with depth (Figure 12).

TABLE 3: Properties of the different soil samples.

	laboratory	onsite
w (%)	19,4	19,0
ρ (Mg/m³)	1,96	1,94
$ρ_d$ (Mg/m³)	1,64	1,63
gravel (%)	0,3	
sand (%)	22,7	
silt (%)	65,2	
clay (%)	11,8	
Soil description	Sandy clayey silt	

TABLE 4: Results of the permeability test on the second test site.

	Guelph	Laboratory	
	k_{fs}	k_s	k_{fs}/k_s
$\bar{x}$ (m/s)	1.1E-08	1.2E-08	2.06
median (m/s)	5.3E-9	4.4E-9	0.58
90th percentile	3.0E-8	3.0E-9	7.10
σ (m/s)	1.3E-08	1.3E-08	
$σ^2$ (m/s)^2	1.6E-16	1.6E-16	
C_v	1.19	1.05	

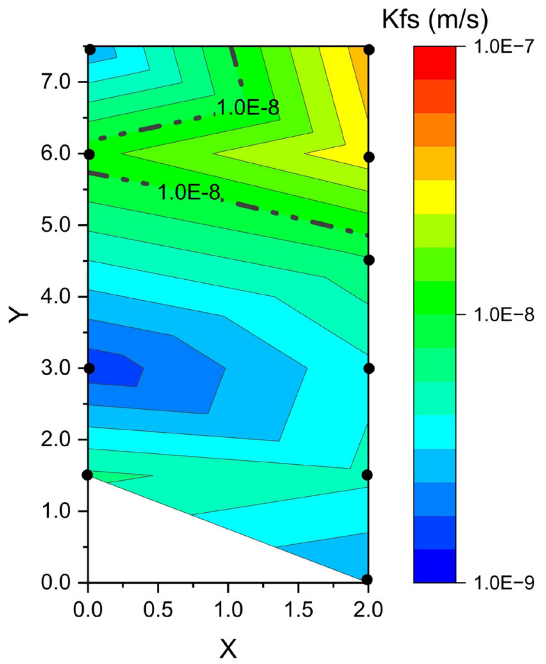

FIGURE 9: Distribution of the hydraulic conductivity determined with Guelph tests on the second test site.

As before, for both laboratory and in-situ permeability tests, the values of the standard deviation and of the coefficient of variation were high but very similar between the two types of tests (Table 4). As expected, the laboratory samples reported different hydraulic conductivity than the on-site tests. Indeed, the two types of tests adopt distinct tools and test conditions to determine the hydraulic conductivity. In particular:

- Difference between sample sizes: the laboratory samples were discs of 4000 mm² in area and 20 mm in height, while the volume sampled on site was a cylinder of 5000 mm² in area and 230 m in height.
- The laboratory tests were carried out at a controlled temperature of 20°C, while it was not possible to control the external temperature on site (ranging from 10°C to 23°C).
- The flow direction in the laboratory tests was vertical, while the on-site test measured the combination of both vertical and horizontal permeabilities.

Despite these disparities in test conditions, the difference between the results of the field and laboratory permeability tests was surprisingly minimal. The mean and medi-

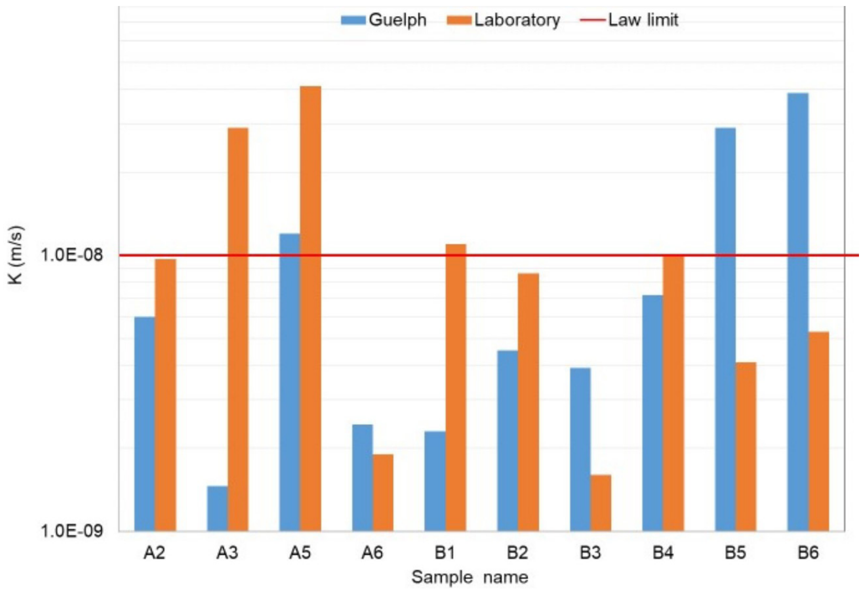

FIGURE 10: Hydraulic conductivity measured on the second test site (ordered by name).

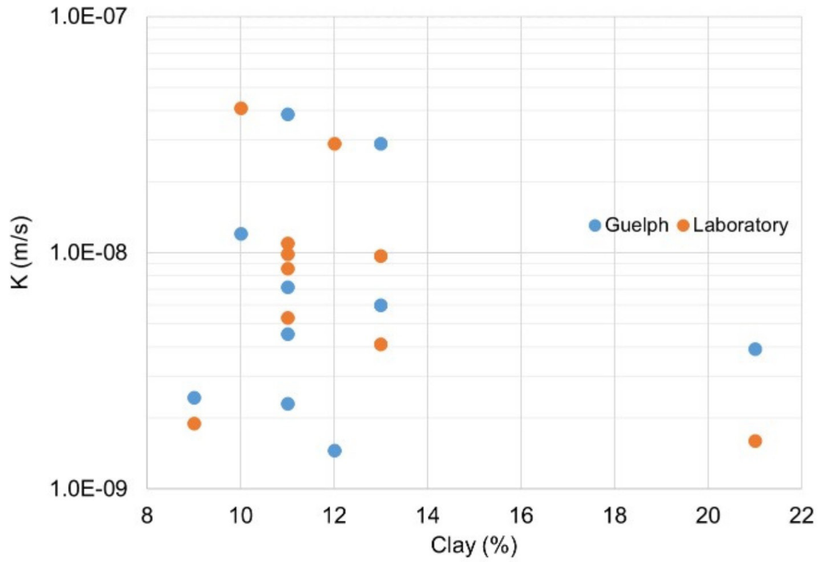

FIGURE 11: Hydraulic conductivity measured on the second test site (ordered by clay fraction).

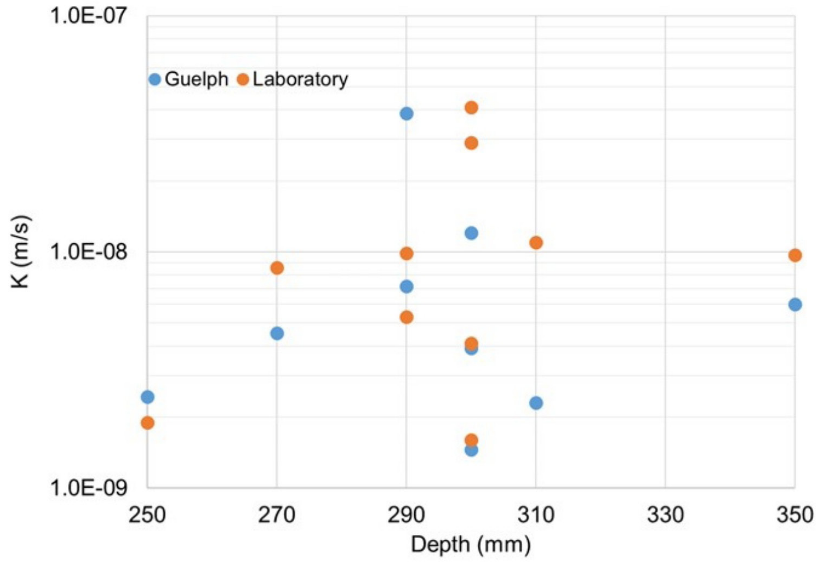

FIGURE 12: Hydraulic conductivity measured on the second test site (ordered by depth).

an k_{fs}/k_s ratios are 2.06 and 0.58, respectively, values that point to the existence of some outliers (Table 4).

A reference bold line, representing the equality between the hydraulic conductivity obtained in the laboratory and in situ, was inserted diagonally in the Figure 13. Other dashed lines, drawn in the same figure, represent the percentual deviation of the Guelph hydraulic conductivity from the above-mentioned reference line. The comparison between laboratory and Guelph hydraulic conductivity data shows a good agreement with some outliers.

Hydraulic conductivity data used in Bland-Altman plot were log-transformed since the hydraulic conductivity generally follows lognormal distribution (Loáiciga, 2015). Figure 14 shows a negative close to zero bias, the width of the 95% upper and lower limits and the absence of an evident trend between the difference and the mean.

Finally, in Figure 15 the k_{fs}/k_s ratio is shown as a function of the clay percentage and is mostly less than unity. In conclusion, considering the significant differences in procedures and conditions between laboratory and in situ permeability tests, the results are remarkably similar, and the Guelph permeameter provided very reliable results.

3. CONCLUSIONS

In the present study, the Guelph permeameter was tested on two testing areas, located on the provisional cover of the Grumolo delle Abbadesse MSW landfill. The mineral liner of the capping system was composed of clayey soils excavated in the landfill site. On the first testing area, 24 hydraulic conductivity tests were performed with a Guelph permeameter. On the second testing area 12 cylindrical samples were collected for laboratory analysis and hydraulic conductivity

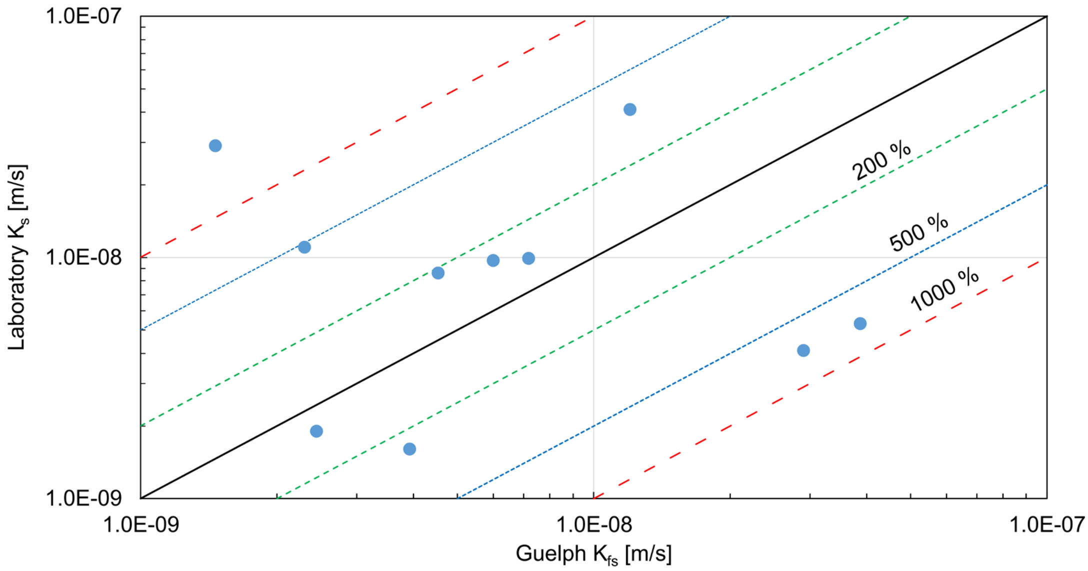

FIGURE 13: Hydraulic conductivity measured on the second test site and in laboratory.

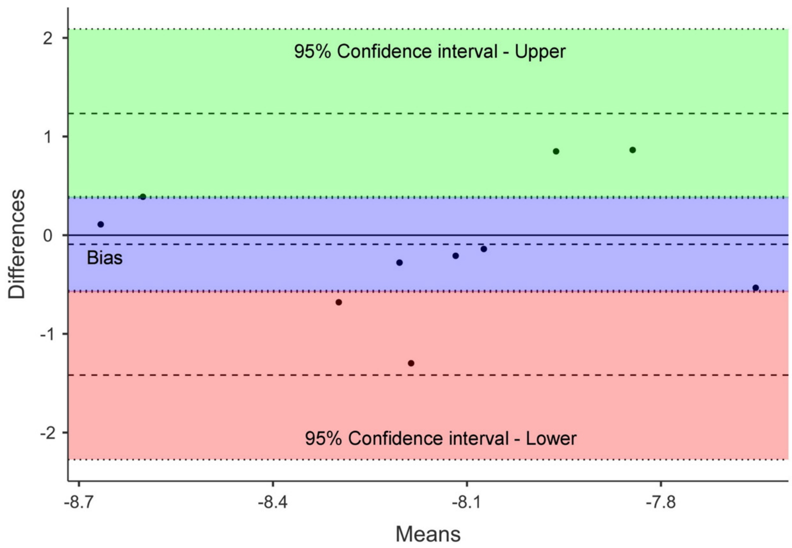

FIGURE 14: Bland-Altman plot between data measured on the second test site and in laboratory.

tests with the Guelph permeameter were performed in the holes made for the sample collection. Two in-situ density tests were also carried out. In the laboratory, sieve analyses and falling head permeability tests were performed.

The main purpose of the first test field was to evaluate reliability and reproducibility of the results obtained with the Guelph permeameter. The experimental results confirm this attitude; if the investigated soil is homogeneous enough, the hydraulic conductivity remains in a range comparable to that of laboratory tests. A greater dispersion of the values was found in the presence of sandy and clayey lenses, detected visually in some points of the investigated area (figure 6) which made the tested soil non-homogeneous.

The purpose of the second testing area was to evaluate the difference between hydraulic conductivities determined with the Guelph permeameter tests and those obtained from laboratory permeability tests.

On this second site, the soil was more homogeneous than on the first one and was classified as a sandy clayey silt. In situ density tests were found to be consistent with laboratory values. In this second test, given the greater accuracy in the selection of soils so that their homogeneity was granted, hydraulic conductivities were more than an order of magnitude lower than in the first test. Although the in situ and laboratory permeability tests differed in terms of test conditions and type of instrumentation, the difference in hydraulic conductivity values determined between corresponding samples was minimal.

In conclusion, the experiments performed with the Guelph permeameter and their statistical processing show its reliability, making it an instrument not only cheap and easy to use, but also reliable if used with the appropriate precautions. In particular, the Guelph permeameter becomes a valid alternative to laboratory permeability tests to

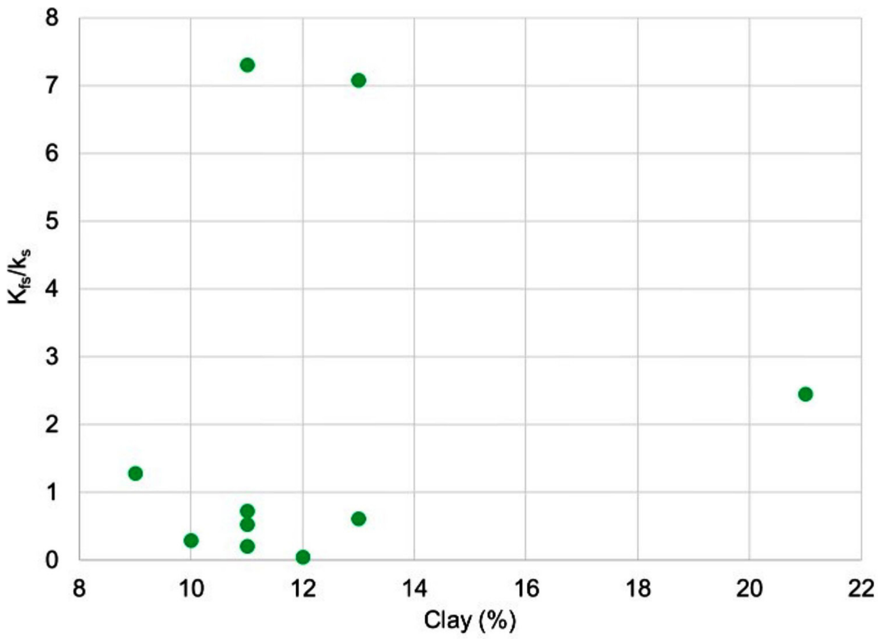

FIGURE 15: Ratio of on-site and laboratory hydraulic conductivities vs clay fraction.

define the permeability of compacted mineral layers quickly and precisely in landfills. The Guelph permeameter can be used with the aim of intervening during the construction of the barrier without slowing down the construction processes. Based on the values of the hydraulic conductivity detected on-site and according to the limits imposed by the regulation, the soil properties can be quickly corrected by adding or removing water or by soil mixing.

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REFERENCES

Bagarello, V., & Iovino, M. (2010). Conducibilità idraulica del suolo: Metodi di misura nelle applicazioni idrologiche. Hoepli.

Braždžionytė, J., & Macas, A. (2006). Bland–Altman analysis as an alternative approach for statistical evaluation of agreement between two methods for measuring hemodynamics during acute myocardial infarction. Medicina, 43(3), Article 3. https://doi.org/10.3390/medicina43030025

Elrick, D. E., & Reynolds, W. D. (1992). Methods for Analyzing Constant-Head Well Permeameter Data. Soil Science Society of America Journal, 56(1), 320–323. https://doi.org/10.2136/sssaj1992.03615995005600010052x

Elrick, D. E., Reynolds, W. D., & Tan, K. A. (1989). Hydraulic Conductivity Measurements in the Unsaturated Zone Using Improved Well Analyses. Groundwater Monitoring & Remediation, 9(3), 184–193. https://doi.org/10.1111/j.1745-6592.1989.tb01162.x

European Council. (1999). Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. European Council. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01999L0031-20180704

European Council. (2018). Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste. European Council. https://eur-lex.europa.eu/eli/dir/2018/850/oj

Fallico, C., Migliari, E., & Troisi, S. (2006). Comparison of three measurement methods of saturated hydraulic condutivity. Hydrology and Earth System Sciences Discussions, 3(3), Article 3.

Feki, M., Ravazzani, G., Barontini, S., Ceppi, A., & Mancini, M. (2020). A comparative assessment of the estimates of the saturated hydraulic conductivity of two anthropogenic soils and their impact on hydrological model simulations. Soil and Water Research, 15(3), 135–147. https://doi.org/10.17221/33/2019-SWR

Fodor, N., Sándor, R., Orfanus, T., Lichner, L., & Rajkai, K. (2011). Evaluation method dependency of measured saturated hydraulic conductivity. Geoderma, 165(1), Article 1.

Gallichand, J., Madramootoo, C. A., Emight, P., & Barrington, S. F. (1990). An evaluation of the Guelph permeameter for measuring saturated hydraulic conductivity. Transactions of the ASAE, 33(4), 1179–1184.

Ghosh, B., Pekkat, S., & Yamsani, S. K. (2019). Evaluation of Infiltrometers and Permeameters for Measuring Hydraulic Conductivity. Advances in Civil Engineering Materials, 8(1), 20180056. https://doi.org/10.1520/ACEM20180056

ISO 17892-11:2019. (2019). Geotechnical investigation and testing—Laboratory testing of soils—Part 11: Permeability tests (ISO 17892-11:2019). International organization for standardization.

Jačka, L., Pavlásek, J., Kuráž, V., & Pech, P. (2014). A comparison of three measuring methods for estimating the saturated hydraulic conductivity in the shallow subsurface layer of mountain podzols. Geoderma, 219, 82–88.

Koppi, A. J., & Geering, H. R. (1986). The preparation of unsmeared soil surfaces and an improved apparatus for infiltration measurements. Journal of Soil Science, 37(2), Article 2. https://doi.org/10.1111/j.1365-2389.1986.tb00017.x

Loáiciga, H. A. (2015). Probability Distributions in Groundwater Hydrology: Methods and Applications. Journal of Hydrologic Engineering, 20(5), Article 5. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001061

Moraci, N., Busana, S., Cortellazzo, G., Favaretti, M., Mandaglio, M. C., & Schepis, M. (2018). Design and construction of a compacted clay liner in cover system of a municipal solid waste (MSW) landfill using nonstandard procedures. Canadian Geotechnical Journal, 55(8), Article 8. https://doi.org/10.1139/cgj-2017-0371

Reynolds, W. D. (1986). The Guelph Permeameter method for in situ measurement of field-saturated hydraulic conductivity and matric flux potential. [Ph.D. Dissertation.]. University of Guelph, Guelph, Ontario, Canada.

Reynolds, W. D., & Elrick, D. E. (1985). In situ measurement of field-saturated hydraulic conductivity, sorptivity, and the α-parameter using the Guelph permeameter. Soil Science, 140(4), 292–302.

Reynolds, W. D., & Elrick, D. E. (1987). A laboratory and numerical assessment of the Guelph permeameter method. In Soil Science (Vol. 144, Issue 4, pp. 282–299). https://journals.lww.com/soilsci/fulltext/1987/10000/a_laboratory_and_numerical_assessment_of_the.8.aspx

Reynolds, W. D., Elrick, D. E., & Clothier, B. E. (1985). The constant head well permeameter: Effect of unsaturated flow. Soil Science, 139(2), 172–180.

Reynolds, W. D., Elrick, D. E., & Topp, G. C. (1983). A reexamination of the constant head well permeameter method for measuring saturated hydraulic conductivity above the water table1. Soil Science, 136(4), 250.

Reynolds, W. D., & Lewis, J. K. (2012). A drive point application of the Guelph Permeameter method for coarse-textured soils. Geoderma, 187–188, 59–66. https://doi.org/10.1016/j.geoderma.2012.04.004

Reynolds, W. D., & Topp, G. C. (2008). Soil water analyses:principles and parameters. Soil Sampling and Methods of Analysis, 913–937.

Rezaei, M., Seuntjens, P., Shahidi, R., Joris, I., Boënne, W., Al-Barri, B., & Cornelis, W. (2016). The relevance of in-situ and laboratory characterization of sandy soil hydraulic properties for soil water simulations. Journal of Hydrology, 534, 251–265.

Soto, M. A. A., & Kiang, C. H. (2018). Avaliação da condutividade hidráulica em dois usos do solo na região central do Brasil. Revista Brasileira de Ciências Ambientais (Online), 47, 1–11. https://doi.org/10.5327/Z2176-947820180169

Xiang, J., Scanlon, B. R., Mullican, W. F., Chen, L., & Goldsmith, R. S. (1997). A multistep constant-head borehole test to determine field saturated hydraulic conductivity of layered soils. Advances in Water Resources, 20(1), Article 1. https://doi.org/10.1016/S0309-1708(96)00017-6

Zhang, Z. F., Groenevelt, P. H., & Parkin, G. W. (1998). The well-shape factor for the measurement of soil hydraulic properties using the Guelph Permeameter. Soil and Tillage Research, 49(3), 219–221. https://doi.org/10.1016/S0167-1987(98)00174-3