CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2026; 36 (3): 0089-0101
DOI: 10.59440/ceer/231605
Original Research Article

ASSESSMENT OF THE SIGNIFICANCE OF MOISTURE VARIATIONS IN CONSTRUCTION SOILS INVESTIGATED USING A LIGHT WEIGHT DEFLECTOMETER: AN EXPERIMENTAL STUDY ON FINE SANDS AND SANDY SILTS/SANDY CLAYS

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Abstract

In situ investigations of construction subsoil are a key component of engineering site investigation for infrastructure and building projects. The light weight deflectometer method (LWD) is becoming increasingly popular owing to its rapid measurement procedure, ease of use, and high mobility during investigations. This study focused on determining the influence of moisture content in the near-surface soil layer, down to approximately 1 m below ground level, on subsoil stiffness, expressed as the dynamic deformation modulus (E_{vd}). The investigations were carried out in two measurement campaigns, before and after artificial irrigation equivalent to 6 mm of rainfall, on two experimental plots composed of coarse-grained fine sand (fSa) and fine-grained sandy silt/sandy clay (saSi/saCl). The obtained results demonstrated a clear influence of moisture content on the E_{vd} modulus. For the fSa plot, E_{vd} decreased by 18%, with an average increase in moisture content of approximately 8 percentage points. In contrast, for the plot composed of saSi/saCl soils, E_{vd} decreased by approximately 41%, with an average change in moisture content of approximately 2 percentage points. These contrasting results indicate a stronger response of fine-grained soils to even small changes in their moisture content, as well as their different sensitivity during LWD testing. The study provides a controlled, plot-scale quantification of moisture-induced changes in LWD-derived stiffness in two contrasting natural subsoils. Furthermore, the findings show that near-surface moisture conditions should be considered during geological and engineering site investigations to avoid an incorrect assessment of foundation conditions.

Keywords: *in situ* testing, soil stiffness assessment, moisture variation, soil deformability, geotechnical investigation

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1. INTRODUCTION

The light weight deflectometer (LWD) is a portable device widely used for the rapid assessment of the dynamic stiffness of near-surface soil layers, particularly in earthworks and geotechnical quality-control applications (Fleming et al., 2007; Duddu & Chennarapu, 2022). Specifically, in Germany, dynamic plate load testing and its application in earthworks are addressed by ZTV E-StB 09 and TP BF-StB Part B 8.3 (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2012; Forschungsgesellschaft für Straßen- und Verkehrswesen, 2018). The LWD method is based on the application of a transient load and the measurement of the resulting deflection of the tested soil surface. The measurements enable the determination of the dynamic deformation modulus (E_{vd}) and generally characterise the soil to an approximate depth of 50 cm. The E_{vd} modulus characterises the deformation response and dynamic stiffness of the tested near-surface soil layer. In construction practice, it is commonly used as a quality-control parameter supporting the assessment of soil compaction or consistency. However, E_{vd} should not be interpreted as a direct measure of soil strength or ultimate bearing capacity, as stiffness and strength represent distinct mechanical properties (Atkinson, 2007). The E_{vd} modulus is generally determined using a simplified Boussinesq solution for an elastic half-space (Duddu & Chennarapu, 2022):

$$E_{vd} = \frac{\frac{F}{a} r(1-\nu^2) f_r}{\omega} \tag{1.1}$$

where: E_{vd} – dynamic deformation modulus [MPa], r – radius of the loading plate [mm], ν – Poisson's ratio, f_r – plate stiffness factor, ω – deflection of the loading plate measured at its centre [mm], F – applied force [N], a – area of the loading plate [mm^2].

The main advantages of testing with an LWD include the immediate possibility of result verification, ease of transport of the measuring device, simplicity of construction, and the non-invasive nature of the tests. However, E_{vd} values are affected not only by soil compaction or consistency, but also by soil type, moisture content and testing conditions. Therefore, these factors should be considered when interpreting LWD results (Tehrani & Meehan, 2010; Duddu & Chennarapu, 2022; Kuttah, 2023).

In this study, soil moisture content served as the primary comparative parameter for the E_{vd} modulus results, given its significant influence on the mechanical and physical properties of soils in geotechnical investigations (Mouazen et al., 2002; Tehrani & Meehan, 2010; Rahardjo et al., 2019). Similar studies have previously been conducted, among others, by Pezowicz and Choma-Moryl (2015) and Duddu and Chennarapu (2022). An increase in moisture content leads to a reduction in cohesion, as well as a decrease in Young's modulus and Poisson's ratio, which consequently reduces soil stiffness and may result in attenuation of stress distribution within the soil medium (Mouazen et al., 2002). Consequently, failure to account for potential variations in the moisture content of the subsoil during geotechnical investigations using LWD may lead to inappropriate design decisions and, as a result, to potential damage to infrastructure (Gorączko et al., 2020). Previous studies have demonstrated that increasing moisture content generally results in lower LWD-derived E_{vd} values, although the magnitude of this response depends on soil characteristics and testing conditions (Tehrani & Meehan, 2010; Duddu & Chennarapu, 2022; Kuttah, 2023). Therefore, the influence of moisture content on changes in the E_{vd} modulus was examined under controlled conditions for two soil types: fine sands (fSa) and sandy silts/sandy clays (saSi/saCl).

The contribution of the present study is not the identification of this phenomenon itself, but its quantitative field assessment in two contrasting natural subsoils subjected to the same applied water depth under a controlled field-wetting protocol. Particular attention was paid to the magnitude and spatial variability of changes in LWD-derived E_{vd} and to the practical consequences for the interpretation of measurements performed under changing moisture conditions.

The specific objectives of this study are: (i) to investigate the effect of increasing moisture content on LWD-derived E_{vd} values in the two analysed soil types; (ii) to assess the statistical significance of differences in LWD-derived E_{vd} values before and after irrigation; and (iii) to compare the magnitude and spatial variability of moisture-induced changes in E_{vd} between the two investigated natural subsoils.

2. MATERIALS AND METHODS

2.1 Experimental research design and fieldwork

The experimental plots were located in Poznań, within the Warta River valley (Fig. 1), on natural soils developed from fluvial deposits represented by fine sand (fSa) and glacial deposits represented by sandy silt/sandy clay (saSi/saCl) (Chmal, 1997). Two flat experimental plots, each covering an area of 100 m^2, were selected after removal of the topsoil layer (Fig. 2). The plots were relatively uniform at the plot scale in terms of their stratigraphic and geomorphological setting.

The investigated soils were classified in accordance with PN-EN ISO 14688-1:2018 (Polski Komitet Normalizacyjny, 2018) as coarse-grained fine sand (fSa) and fine-grained sandy silt/sandy clay (saSi/saCl). The general uniformity of soil conditions within each experimental plot (Fig. 2) was confirmed by a preliminary site investigation and subsequently verified by particle size distribution analysis. Particle size distribution was determined for 18 soil samples, including 9 samples from each experimental plot. At each plot, samples were collected from three boreholes at depths of 20, 40 and 70 cm below ground level. The analyses were conducted in accordance with PN-EN ISO 17892-4:2015 (Polski Komitet Normalizacyjny, 2015b) using sieve and hydrometer methods. The curves presented in Figure 3 represent the mean particle size distributions obtained for the samples collected from each experimental plot. Additionally, for the sandy silt/sandy clay soil, the Atterberg limits were determined, from which the plasticity index (PI) and liquid limit (LL) were evaluated in accordance with PKN-CEN ISO/TS 17892-12:2009 (Polski Komitet Normalizacyjny, 2009). The mean values of these parameters were as follows: PI = 12.3%; LL = 24.9%.

Each experimental plot was divided into twenty rectangular measurement cells, each measuring 2.0 × 2.5 m, with one LWD measurement point located within each cell (Fig. 2). Three soil-sampling areas, designated Borehole 1 (BH1), Borehole 2 (BH2), and Borehole 3 (BH3), were distributed across each plot.

Two moisture conditions were considered: natural moisture conditions and conditions following irrigation of the soil with 600 L of tap water per experimental plot (equivalent to 6 mm of rainfall), representing moderate-to-heavy precipitation intensity (Podstawczyńska, 2007). For each experimental plot, the investigation was performed in the following sequence: (1) LWD measurements under natural moisture conditions, (2) collection of soil samples before irrigation, (3) controlled irrigation of the experimental plot, (4) a waiting period following irrigation, (5) repeated LWD measurements at the same twenty measurement points, and (6) collection of soil samples after irrigation.

Following irrigation, the post-irrigation LWD measurements were performed after approximately 2 h at the fine sand plot and 12 h at the sandy silt/sandy clay plot. Soil sampling was subsequently conducted to determine moisture content and its spatial variability within each experimental plot. Moisture-content samples were collected from depths of 10, 20, 30, 40, 50, 70, 90, and 100 cm below ground level. The collected soil samples were immediately sealed in airtight polyethylene bags and subsequently subjected to moisture content determination. Because moisture sampling was destructive, the pre- and post-irrigation samples at each BH1-BH3 sampling area were collected from separate adjacent boreholes located no more than 0.5 m apart. E_{vd} modulus measurements were performed using the same LWD device (TERRATEST 4000 STREAM; TERRATEST GmbH, Nassenheide, Germany) under constant testing parameters. Each measurement was conducted according to the previously established LWD measurement grid (Fig. 2). Boreholes and LWD tests were performed directly on the investigated soil layer after removal of the topsoil layer.

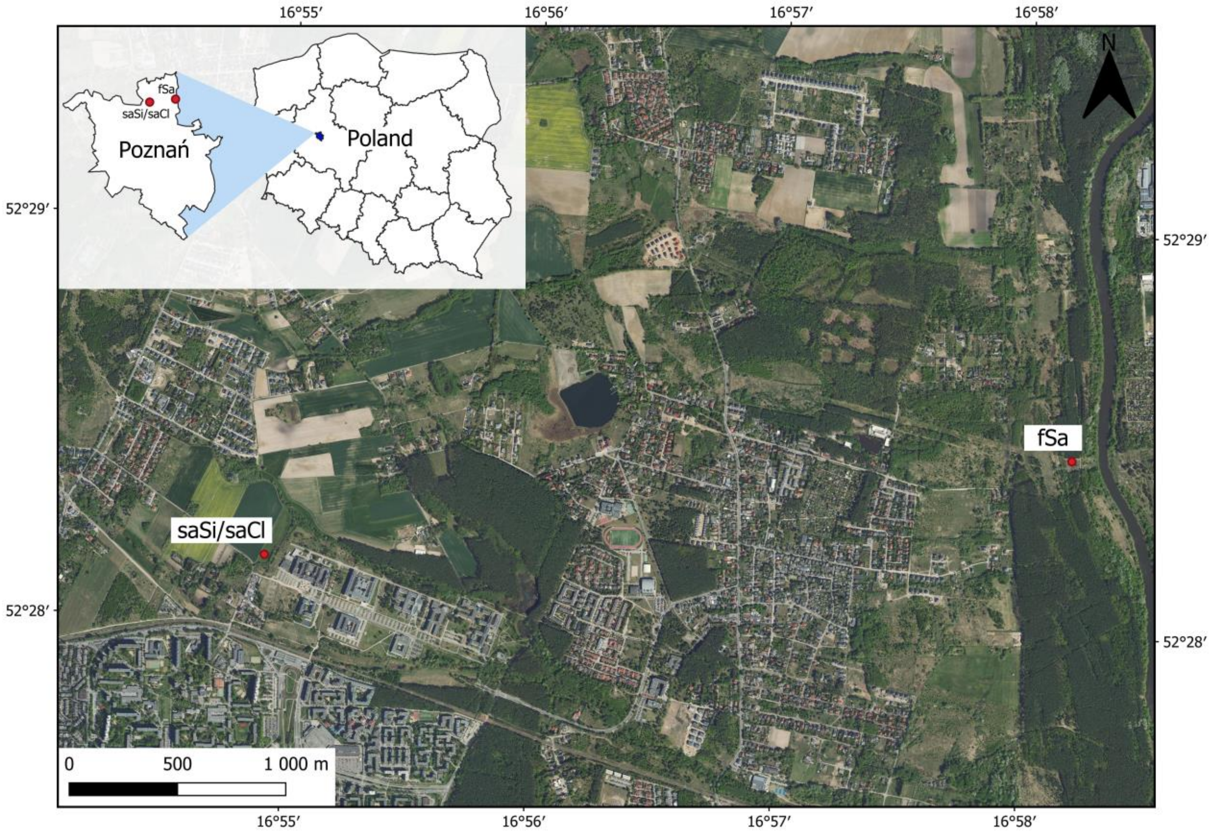

Fig. 1. Locations of the experimental plots in northern Poznań

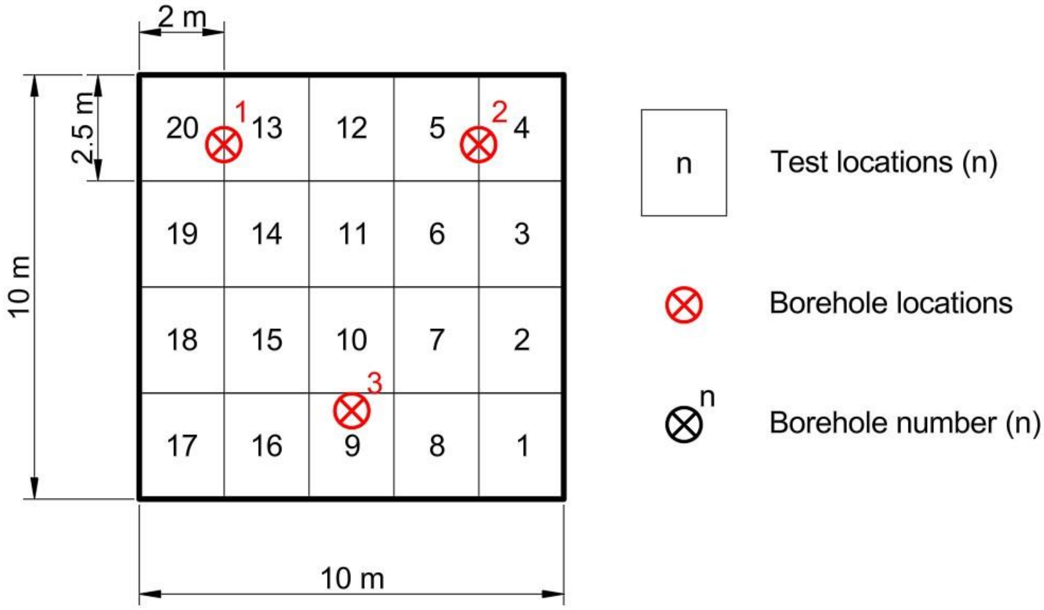

Fig. 2. Testing layout on the experimental plot

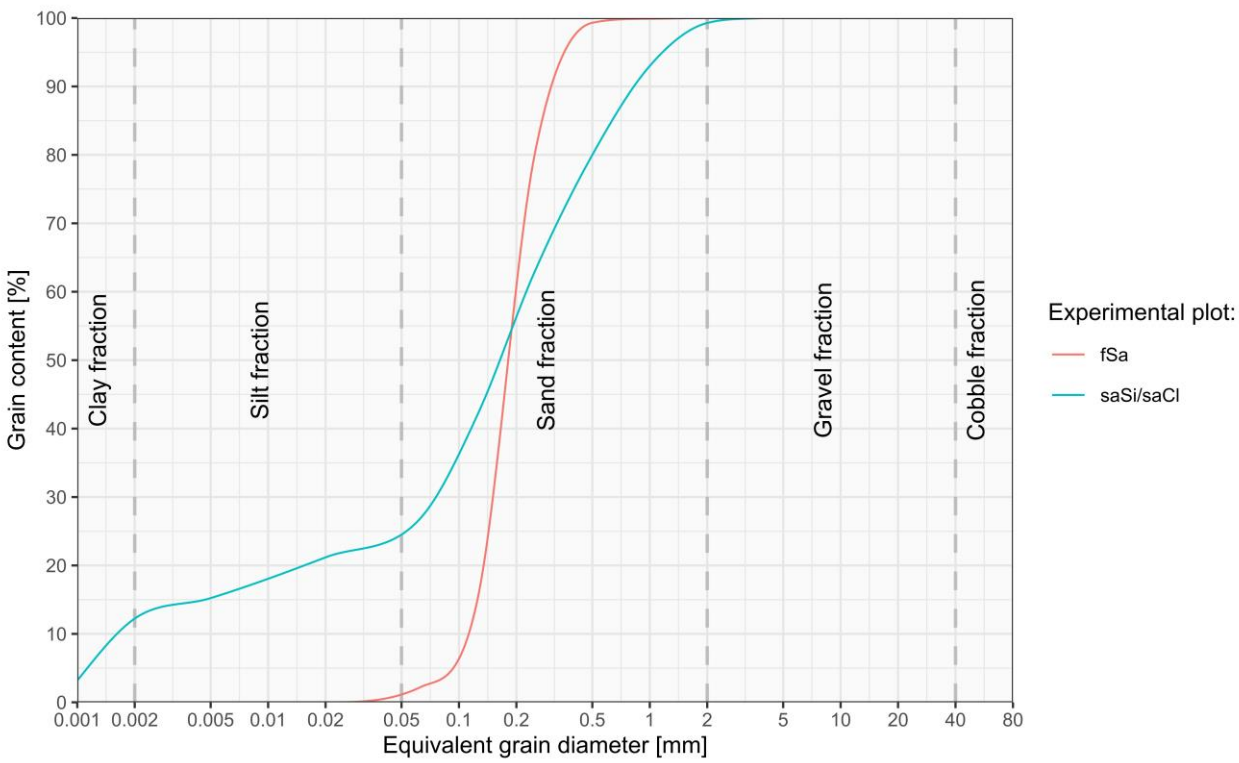

Fig. 3. Mean particle size distribution curves of the soils investigated at the fine sand (fSa) and sandy silt/sandy clay (saSi/saCl) experimental plots

2.2 Determination of moisture content

The moisture content of the analysed soils was determined immediately after sampling under laboratory conditions. The moisture content analyses were conducted in accordance with PN-EN ISO 17892-1:2015 (Polski Komitet Normalizacyjny, 2015a).

2.3 Statistical analysis

The statistical significance of differences between measurement series was assessed using the Wilcoxon signed-rank test (Wilcoxon, 1945). Prior to hypothesis testing, the normality of data distribution was evaluated using the Shapiro-Wilk test at a significance level of $\alpha = 0.05$. The results confirmed that none of the analysed paired datasets exhibited a normal distribution in both compared conditions, thereby justifying the application of a non-parametric test. In addition, for the results obtained from LWD measurements, basic descriptive statistics were calculated, including measures of central tendency (mean and median) and dispersion (minimum, maximum, and standard deviation). The data were further visualised using raincloud plots (Allen et al., 2021). All statistical analyses were conducted in R (R Core Team, 2025), version 4.5.2, and the visualisations were prepared using the ggplot2 package (Wickham, 2016).

3. RESULTS

3.1 Fine sands experimental plot

The influence of soil moisture on E_{vd} modulus results was assessed by analysing changes in moisture content before and after irrigation. A clear increase in moisture content was observed in all analysed fSa profiles (Fig. 4A). The most pronounced changes occurred in the upper parts of the profiles. In BH1 and BH3, the increase in moisture content was clearly evident down to a depth of 50 cm below ground level, whereas in BH2 it extended to a depth of 30 cm below ground level. The mean moisture content to a depth of 50 cm below ground level, corresponding to the Effective Measurement Depth (EMD) of the LWD, increased from 7.2% to 17.4% in BH1, from 4.9% to 9.7% in BH2, and from 5.3% to 14.4% in BH3. For the entire fSa experimental plot, the mean moisture content within the EMD increased from 5.8% to 13.8%. Below the maximum effective measurement depth of LWD, changes in soil moisture were less pronounced (Fig. 4A), and the mean moisture content for the entire experimental plot within the 50-100 cm depth interval increased only slightly, from 4.2% to 4.8%.

The analysis performed using LWD indicates a significant influence of moisture content on the obtained results. The initial values of the E_{vd} modulus ranged from 11.3 to 17.8 MPa. The mean E_{vd} value was 13.6 MPa with a standard deviation of 1.8 MPa (Table 1). Following soil irrigation and an average increase in moisture content within the LWD influence zone from 5.8% to 13.8%, a clear decrease in E_{vd} values was observed (Figs. 5A and 6). The mean E_{vd} value decreased to 11.1 MPa, with a standard deviation of 2.2 MPa and values ranging from 7.6 to 16.3 MPa. On average, for the entire fSa experimental plot, E_{vd} decreased by 2.5 MPa, corresponding to an 18% reduction. A slight increase ($\Delta E_{vd} = 0.7$ MPa) was observed at only one measurement point (Fig. 5A). The Wilcoxon signed-rank test confirmed that the changes in the E_{vd} modulus before and after irrigation were highly statistically significant ($p \leq 0.001$) (Fig. 6).

3.2 Sandy silts/sandy clays experimental plot

The soil moisture content within the saSi/saCl experimental plot exhibited more heterogeneous changes after irrigation compared to the fSa plot (Fig. 4B). A clear increase in moisture content to a depth of 50 cm below ground level was observed in BH2 and BH3 (Fig. 4B), where moisture increased from 10.2% to 13.2% in BH2 and from 7.8% to 12.6% in BH3. In the BH1 sampling area, a decrease in moisture content after irrigation was observed at depths of 0-30 cm, while an increase was recorded only at depths of 40 and 50 cm below ground level (Fig. 4B). Nevertheless, the mean moisture content within the EMD of the LWD for the saSi/saCl experimental plot increased from 9.5% to 11.5%.

The saSi/saCl experimental plot generally showed a greater decrease in the E_{vd} modulus compared to the fSa plot (Figs. 5 and 6). The mean E_{vd} value prior to irrigation was 21.2 MPa with a standard deviation of 4.3 MPa and values ranging from 12.6 to 29.6 MPa. After irrigation, the mean E_{vd} decreased to 12.5 MPa with a standard deviation of 4.8 MPa and values ranging from 7.1 to 24.4 MPa (Table 1). The mean decrease in E_{vd} for the entire plot was 8.7 MPa, corresponding to an approximate 41% reduction. A decrease in E_{vd} was observed in 19 out of 20 measurements, while at one measurement point the value remained unchanged (Fig. 5B). The Wilcoxon signed-rank test indicated a highly significant difference between E_{vd} values obtained before and after irrigation ($p \leq 0.001$) (Fig. 6).

Table 1. Descriptive statistics of the dynamic deformation modulus (E_{vd}) obtained from LWD measurements before and after soil irrigation for fine sands and sandy silts/sandy clays

Parameter	Fine sand (fSa)		Sandy silt/Sandy clay (saSi/saCl)	
Unit	MPa			
Irrigation condition	Before	After	Before	After
Minimum	11.3	7.6	12.6	7.1
Maximum	17.8	16.3	29.6	24.4
Mean	13.6	11.1	21.2	12.5
Median	13.5	10.8	21.6	10.7
Standard deviation	1.8	2.2	4.3	4.8

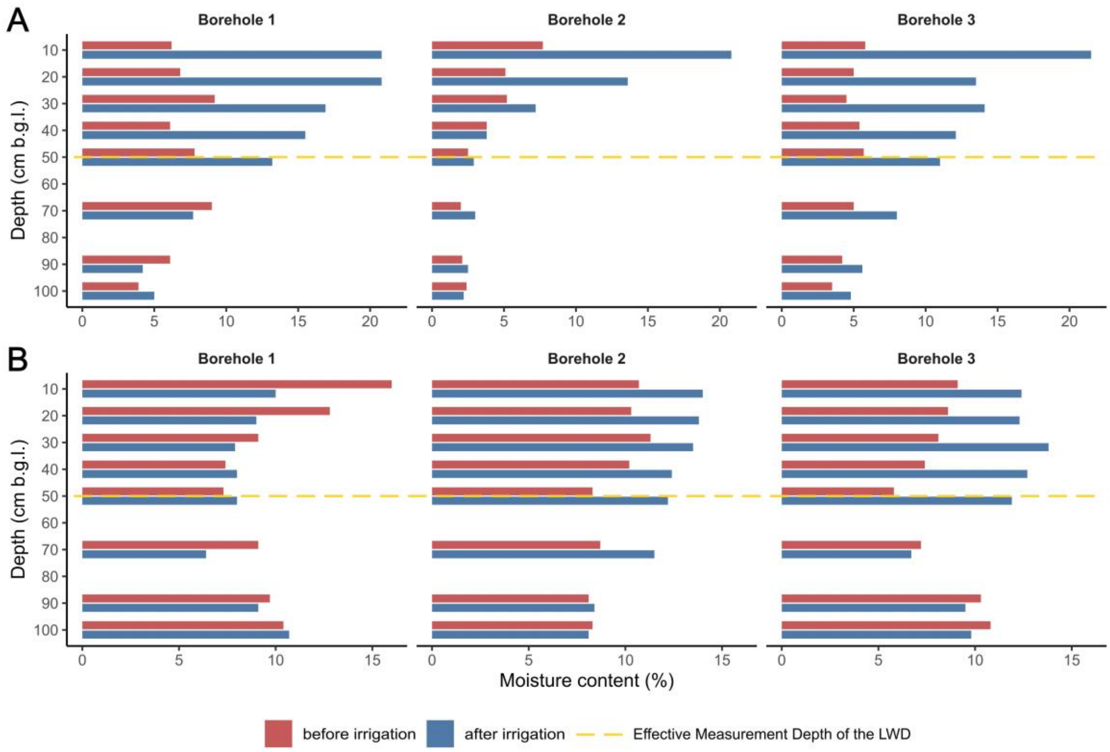

Fig. 4. Soil moisture content before and after controlled irrigation, with the EMD of the LWD indicated: (A) fSa; (B) saSi/saCl

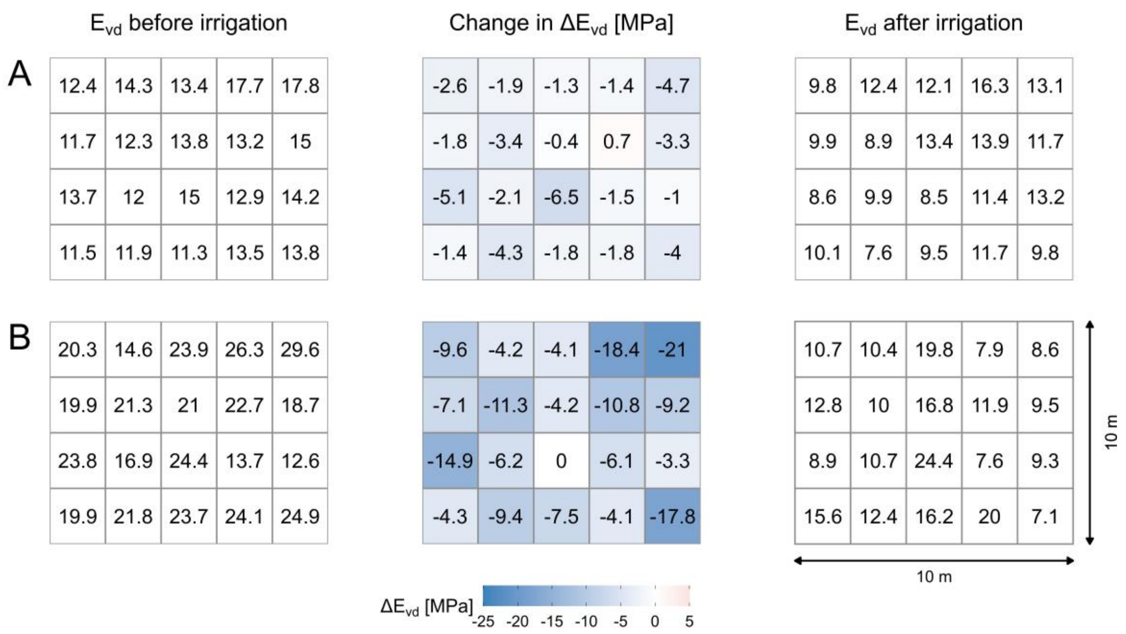

Fig. 5. Comparison of E_{vd} values obtained from LWD testing before and after subsoil irrigation for (A) fine sands (fSa) and (B) sandy silts/sandy clays (saSi/saCl)

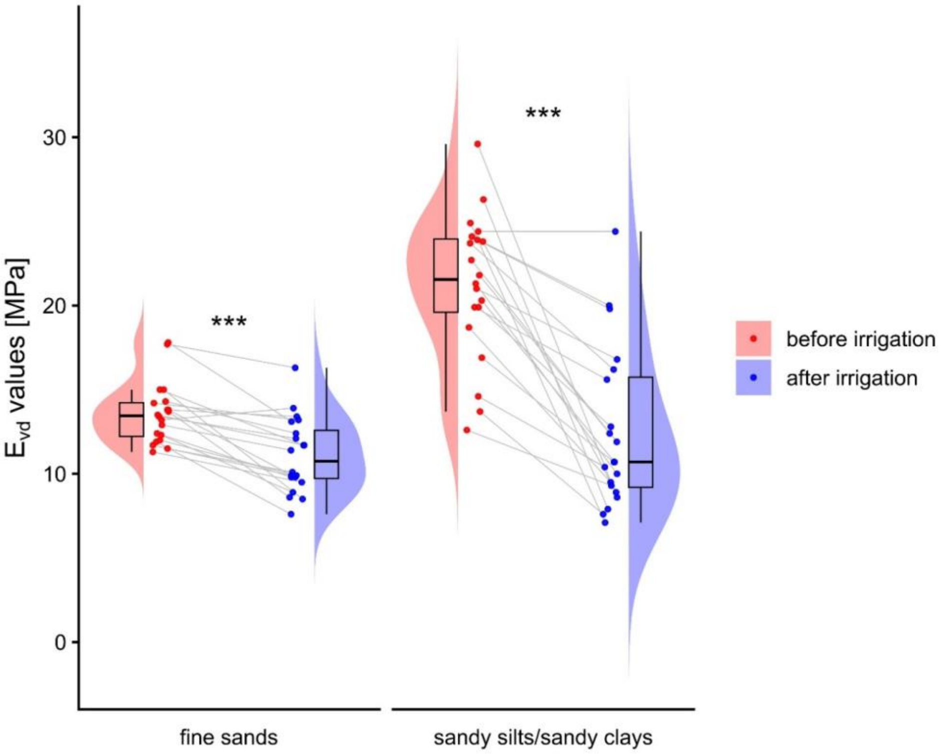

Fig. 6. Raincloud plots illustrating the distribution of E_{vd} values before and after soil irrigation, their changes between measurement series, and the results of the Wilcoxon signed-rank test, where NS denotes not significant ($p > 0.05$), * significant ($p \leq 0.05$), ** more significant ($p \leq 0.01$), and *** highly significant ($p \leq 0.001$)

4. DISCUSSION

Determining the influence of changes in subsoil moisture content on its deformability characteristics, assessed using an LWD, is an important issue not only from a scientific perspective, but above all from a practical one (e.g., Fleming et al., 2007; Tehrani & Meehan, 2010; Kavussi et al., 2019; Kuttah, 2023). The results obtained from the two experimental test plots indicate a significant effect of moisture-content changes in fSa and saSi/saCl soils on E_{vd} values. At the same time, they are consistent with findings previously reported by other authors (e.g., Tehrani & Meehan, 2010; Kuttah, 2023). E_{vd} values decrease with increasing subsoil moisture content. In the sandy subsoil (fSa), an average increase in moisture content from ~6% to ~14% resulted in an 18% decrease in E_{vd}, whereas in the clayey subsoil (saSi/saCl), an average increase in moisture content from ~9.5% to ~11.5% resulted in a reduction of more than 40%. These differences indicate that the response of the subsoil to irrigation was strongly dependent on lithology and on the spatial variability of moisture conditions within the test plots.

The obtained results suggest that the infiltration mechanism did not proceed in the same way in the two experimental plots. The plot composed of fSa was characterised by a more uniform increase in moisture content after irrigation, indicating a more homogeneous response of the sandy subsoil. By contrast, within the saSi/saCl plot, the distribution of moisture content and changes in E_{vd} was clearly more spatially variable. This was particularly evident in the BH1 area, where locally lower moisture contents were recorded after irrigation in the upper part of the soil profile. Because the sampling procedure was destructive, the pre- and post-irrigation profiles were obtained from separate adjacent boreholes located no more than 0.5 m apart and may therefore have differed owing to local spatial variability. Local textural and structural heterogeneity (Radaszewski & Wierzbicki, 2019) may therefore have resulted in differences in initial moisture content, pore structure, and hydraulic properties between the two samples collected (Bouwer, 2002; Nimmo, 2006). In fine-grained soils, differences in water retention associated with the presence of clay fractions and clay minerals may also be significant (Kumari & Mohan, 2021), as well as the possibility of lateral water flow above layers with reduced hydraulic conductivity (Bouwer, 2002). In addition, during the 12-h waiting period, the applied water may have been redistributed vertically and laterally within the fine-grained soil. Thus, the pattern observed at BH1 may reflect the combined effects of spatial variability and heterogeneous water redistribution.

The stronger response of the saSi/saCl subsoil compared with fSa may be related to the different structure and hydro-mechanical properties of fine-grained soils. Fine-grained soils generally contain a higher proportion of the <0.05 mm fraction, which substantially limits hydraulic conductivity (Benson & Trast, 1995; Kaczyński & Grabowska-Olszewska, 1997). Under such conditions, pore-water pressure may increase locally, and effective stress may be reduced (Rahardjo et al., 2019), which consequently leads to a decrease in subsoil stiffness (Latimer et al., 2023). In addition, the presence of clay particles (d < 0.002 mm), characterised by high hydrophilicity, promotes the adsorption of water molecules on the surfaces of clay minerals (Kumari & Mohan, 2021). This leads to the formation of hydration layers that increase the distance between particles, weaken interparticle interactions, and consequently reduce cohesion and increase the susceptibility of the soil to deformation (Schmitz, 2006).

The results indicate that artificial wetting equivalent to a rainfall depth of approximately 6 mm may significantly alter the stiffness characteristics of subsoil assessed using an LWD, particularly immediately after wetting. Under such conditions, measurements may lead to an underestimated assessment of subsoil stiffness if the current moisture state is not taken into account during interpretation. This is particularly important in the case of fine-grained soils, which in the present experiment showed greater sensitivity to moisture-content changes than coarse-grained soils. The main limitation of the study was the measurement range of the LWD, extending approximately 50 cm into the soil profile, which substantially hindered the interpretation of mechanisms affecting the investigated soils below the EMD. In engineering practice, it is therefore necessary to consider current moisture conditions, including rainfall-related conditions, when interpreting E_{vd} values and, where necessary, to apply supplementary methods with a greater depth range than the LWD. The obtained results indicate that the interpretation of LWD measurements after a rainfall event should consider not only the mean change in moisture content, but also its spatial variability within the investigated area. Moreover, it may be advisable to avoid LWD measurements directly after moderate or intense rainfall events. To obtain results with the highest possible reliability, testing should be postponed until the investigated soils return to moisture conditions close to their average state. In sandy soils, this period may last several tens of hours, whereas in finer-grained or clay-rich soils it may extend to several days, depending on soil texture, hydraulic conductivity, drainage conditions and antecedent moisture content (Jabro et al., 2009; An et al., 2018).

5. CONCLUSIONS

1. An increase in subsoil moisture content, including that caused by rainfall, may lead to modifications of the mechanical and physical parameters of soils, including a decrease in E_{vd} values determined using an LWD.

2. Under the soil-specific infiltration conditions observed during the experiment, the fine-grained sandy silt/sandy clay soils (saSi/saCl) responded considerably more strongly than the coarse-grained fine sand soils (fSa). In saSi/saCl soils, a 2-percentage-point increase in moisture content resulted in a decrease in E_{vd} of more than 40%. In contrast, in fSa, an 8-percentage-point increase in moisture content corresponded to an 18% decrease in E_{vd}. These changes were probably related to soil structure, a higher proportion of fine fractions, lower hydraulic conductivity, spatial redistribution of water within the soil profile and changes in capillary suction in saSi/saCl soils.
3. In the present experiment, artificial wetting equivalent to a rainfall depth of 6 mm was associated with statistically significant reductions in LWD-derived E_{vd} values, particularly in fine-grained soils. Consequently, it may lead to an underestimation of subsoil stiffness if the current moisture state is not taken into account when interpreting *in situ* test results.
4. Due to the limited depth range of the LWD, which is approximately 50 cm below ground level, investigations carried out for construction projects should be supplemented with methods enabling the assessment of soil parameters at greater depths.

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