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Evaluation of the relative density based on flat dilatometer test

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Abstract: Overseeing the relative density of soils in all types of earth structures during both construction and operation is crucial to ensure that these structures attain the necessary density and strength. Especially in linear structures that extend over significant lengths, geotechnical investigations should include planning tests that allow for determining the maximum number of geotechnical parameters, such as cone penetration tests (CPTU) or Marchetti dilatometer tests (DMT). The article presents the *in situ* tests aimed at assessing the relative density of sandy soils. Empirical formulas available in the literature for determining the relative density D_r from DMT gave inconsistent results compared to those obtained from dynamic soundings, especially in the near-surface zone, where high K_D readings significantly overestimate relative density values. Assuming the results of DPL probe tests as reference values, a formula for the compaction index based on DMT soundings has been proposed. In contrast to the formulas commonly used in the literature, the proposed formula for the relative density depends not only on the horizontal stress index $K_{D,}$ but also on the dilatometer modulus E_D.

Keywords: *in situ* test, relative density, noncohesive soils, flat dilatometer

1 Introduction

According to the current law construction (Eurocode 7), every construction project applying for a building permit should include, as needed, the results of geological and engineering research. The documentation that describes the ground conditions of the structure consists of the developed findings from both field and laboratory tests. Field tests have the advantage of being conducted in the natural environment, which can be challenging to replicate in laboratory conditions. Dynamic probing (such as dynamic probing light [DPL], standard penetration test [SPT]), cone penetration tests (CPTU), and Marchetti dilatometer tests (DMT) are widely utilized methods in leading research institutions. Efforts are being made to seek field research methods that minimize the need for multiple types of equipment, while allowing for the broad interpretation of the obtained results (e.g., Jamiolkowski et al., 1991; Młynarek et al., 2018, Młynarek et al., 2021).

One of the key issues in present-day geotechnics involves matters related to establishing correlations between various *in situ* investigation techniques and so-called local correlational dependencies. This task, especially concerning soils in the Polish region, can be considered extremely important, as many companies and scientific centers utilize state-of-the-art *in situ* investigation techniques without calibration studies (Młynarek, 2013). One field test which is commonly used in engineering practice, and the methodology for interpreting parameters is the subject of continuous analysis is DMT (Marchetti, 1980; Marchetti and Monaco, 2018; Rabarijoely et al., 2021). The primary advantage of dilatometer testing is its speed and relatively simple measurement process, which enables the determination of soil parameters.

Compaction control plays a critical role in ensuring the long-term stability and durability of structures constructed on soils, as well as preventing soil settlement, deformation, and other geotechnical problems. Proper compaction helps to increase the load-bearing capacity of the fill, minimize the settlement, and reduce the risk of deformation and failures. The currently observed wide range of possible interpretations of static and dynamic CPTU in noncohesive soils as a function of the results and compaction degree implies that no probe can be treated as a standard yielding "true" D_r value (Ura and Tarnawski, 2014). In such a situation, it may be beneficial to seek correlations between the results of penetration tests and the outcomes of studies directly determining the bearing

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capacity of noncohesive soils, such as DMT (Tarnawski, 2010). Furthermore, many independent variables affect the measured pressures during a DMT, and therefore, the relationships found in the literature generally do not fully determine the actual soil parameters. The correction of relationships known from the literature or the formulation of a new one adapted to local ground conditions seems to be of particular interest. Considering this, the present study attempts to establish a relationship between DMT indices and the relative density. Of course, the results of the research are affected by errors following inability to completely control the ground conditions in which the tests were conducted. The relationship determined in the paper will be limited to the range of relative density that occurred specifically at the examined site, that is, in our case, from D_r 0.3 to 0.80.

There are few verified formulas in the literature for determining relative density based on other case studies. The most commonly used relationship for determining relative density (D_r) based on DMT is the equation derived by Marchetti (1992), which is a function of the wedge resistance (q_d) and the effective vertical stress (σ'_{v0}):

$$D_r = -1.082 + 0.204 \cdot \ln\left(\frac{q_d}{\sigma'_{v0}}\right)^{0.4} \tag{1}$$

where: D_r is the relative density (%), q_d is the wedge resistance (kN), and $'_{v0}$ the effective vertical stress (kPa).

Another relationship, which was presented by Jamiolkowski et al. (2001), connects the horizontal stress index with the relative density and takes the following form:

$$K_D = 0.49^{2.72 \cdot D_r} \tag{2}$$

where K_D is the horizontal stress index (-) and D_r is the relative density (-).

A relationship derived by Mayne (2002) for relative density, which is dependent on the horizontal stress index, is essentially a reflection of the Jamiolkowski equation and yields lower values of soil compaction compared to the original formula. Despite having a different form, the results obtained from these two relationships exhibit a similar trend with a slight displacement from each other:

$$D_r = \left[\frac{1}{40 \cdot (K_D - 1)} + \frac{1}{120}\right]^{-1.0} \tag{3}$$

where D_r is the relative density (%) and K_D is the horizontal stress index (-).

According to the literature, all the above formulas work well for normally consolidated and uncemented soils. An example of another equation, although less commonly used in practice, is provided by Tanaka and Tanaka (1998) from the Ohgishima and Kemigawa sites, where D_r was determined based on high-quality samples collected using the freezing method. This formula takes the following form:

$$D_r = 100 \cdot \left(\frac{K_D - 1}{7}\right)^{0.5} \tag{4}$$

where D_r is the relative density (-) and K_D is the horizontal stress index (-).

For this study, it would be difficult to accurately assess which of the formulas (Eqs 1–4) should be used to determine relative density based on DMT. The methodology of DMT neglects the shear stress factor, and the small deviation of the membrane has only a minor influence on the tested soil. All the relationships mentioned above result in overestimated density values in the near-surface layer, but it should be emphasized that they have a local character and may not necessarily work in our conditions. In 1989, Larsson drew attention to this and proposed introducing corrections to dilatometer indices. The proposed correction applied to the first 2 m of testing depth in organic and cohesive soils and was related to the assessment of the shear strength of these soils. Analyzing the relative density in noncohesive soils based on DMT allows observing similar behavior, that is, high values of horizontal stress index yield very high soil compaction values compared to dynamic probing. This provided another rationale for developing a new relationship that would eliminate the need for additional corrections due to the probing depth.

Based on the above and taking into account results of DPL testing and DMT conducted on a modernized section of a railway embankment, a new relationship was established to assess the relative density (D_r) of sands within the embankment body.

2 Materials and Methods

2.1 *In situ* investigations

To check the compaction of noncohesive soils present in the embankment and its base, as well as the deformation and strength parameters of noncohesive and organic

Figure 1: The DMT unit control during the test (a) and geophysical investigation (b).

soils, DPL testing and DMT were conducted at six selected locations in pairs (i.e., DPL testing with DMT at each location). The use of a DPL to assess the relative density of soil is a well-known method employed in engineering practice for decades (e.g., Meardi, 1971; Borowczyk and Frankowski, 1981; Pinheiro et al., 2018; Gruchot, 2019). Interpreting the results of DPL tests based on the standards issued in Poland can raise several doubts. The value estimated for the relative density D_r may significantly differ depending on the interpretation method applied (Borowczyk and Frankowski, 1981; Hawrysz and Stróżyk, 2015). For the purposes of this study, data from DPL test have been interpreted using the relationship shown in Eq. 5. This formula originating from the Polish standard (PN-B-04452) has been repeatedly verified under local conditions and has become quite firmly established in the awareness of geotechnical engineers who are engaged in *in situ* research and interpretation:

$$D_r = 0.429 \cdot \log N_{10} + 0.071 \quad (5)$$

where D_r is the relative density (-) and N_{10} is the number of blows (-).

DMT requires a little more attention, even though it is already a very popular research tool and engineers have been using it for almost half a century (e.g., Marchetti, 1980; Totani et al., 2001; Rabarijoely, 2018; Nepelski, 2020; Virsis et al., 2023). It consists of measuring the gas pressure acting on the diaphragm of a dilatometer blade (Fig. 1a) at selected subsoil depths. In soil tests, two pressures are usually measured (A and B); they force the center of the membrane to move 0.05 mm to the ground (reading A) and deflect the center of the membrane toward the ground by approximately 1.05 mm (reading B). To extend the dilatometer testing, pressure measurements are sometimes taken as the membrane returns to ground contact (C reading). Readings A, B, and C are corrected for the stiffness of the diaphragm and marked as p_0, p_1, and p_2, respectively. Pressures p_0 and p_1 and the value of the vertical effective stress σ'_{v0} are used to determine the following dilatometer indexes: material index (I_D), horizontal stress index (K_D), and dilatometer modulus (E_D) and pore pressure index (U_D) (Marchetti, 1980).

$$I_D[-] = f(A, B, u_0) = \frac{p_1 - p_0}{p_0 - u_0} \quad (6)$$

$$K_D[-] = f(A, u_0, \sigma'_{v0}, B) = \frac{p_0 - u_0}{\sigma'_{v0}} \quad (7)$$

$$E_D[MPa] = f(A, B) = 34.7 \cdot (p_1 - p_0) \quad (8)$$

$$U_D[-] = f(A, C, u_0, B) = \frac{P_2 - u_0}{P_0 - u_0} \quad (9)$$

where: A, B, C are the pressure readings (bar), p_0, p_1, p_2 the pressures (MPa), σ'_{vo} the *in situ* overburden stress (MPa), and u_0 is the pore water pressure acting in the center of the membrane before insertion of the DMT blade (often assumed as hydrostatic below the groundwater table) (MPa).

Geophysical studies were also conducted with the aim of assessing the homogeneity of the embankment in terms of the material from which it was constructed

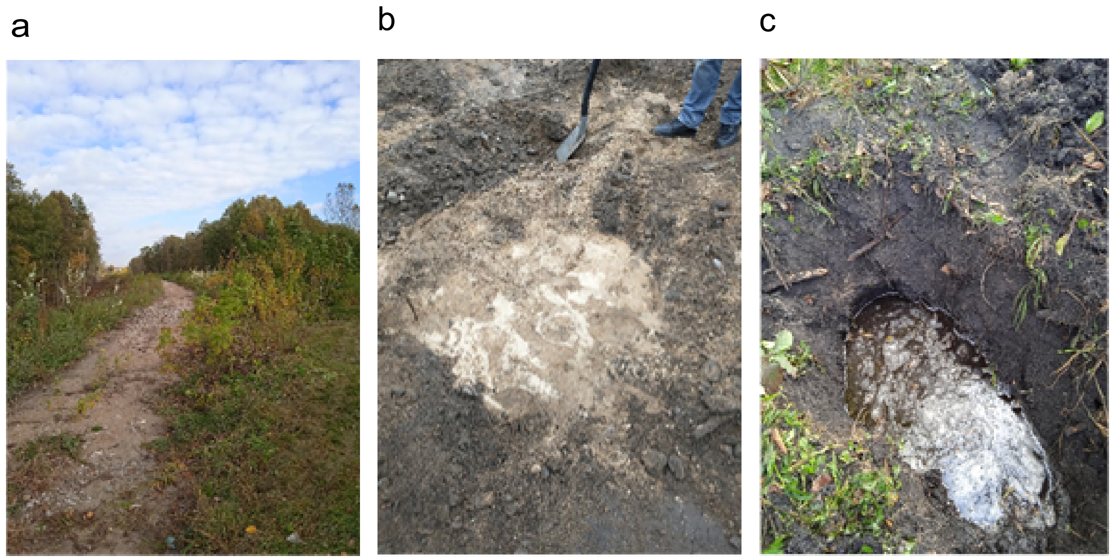

Figure 2: An overall view of the embankment (a), a view after removing the breakstone layer (b), and an excavation at the base of the embankment (c).

(Fig. 1b). The research was conducted in a selected cross section determined based on soundings, supplemented with macroscopic assessment of soil after removing the breakstone, and by performing a research trench at the base of the embankment (Fig. 2). Electrical tomography (ERT) using 32 electrodes in the Wenner array, which was applied in the present study, has been thoroughly described in numerous literature sources such as Reynolds (2011), Koda et al. (2017), and Lech et al. (2020), for example.

2.2 Characteristics of the test site

The area where the research was conducted is a renovated section of a railway embankment located to the north of Warsaw. It is situated within the Warsaw Basin, between the Vistula and Narew rivers. The terrain in the basin consists mainly of flat, relatively folded surfaces that form a part of the floodplain terrace. The morphology of the terrain is closely related to its geological structure, particularly the type of near-surface deposits. The area consists mainly of sandy and sandy-gravel deposits, as well as alluvial clay deposits of the floodplain terrace, with peat and silt locally found in low-lying areas.

The section under study has an embankment with a height of up to 6.5 m and is built of noncohesive soils, mainly medium and fine sands in a medium dense condition ($D_r = 0.35 \div 0.65$) and also, as shown by DPL investigations, in a loose condition ($D_r < 0.35$). Only in the upper part, the embankment soils to a depth of about 1 m are dense ($D_r = 0.65 \div 0.8$). In Figure 2, an overall view of the examined section of the embankment is presented, as well as a view after removing the top layer of breakstone.

Beneath the embankment are organic soils (peats and sandy and clayey silts) with a maximum thickness of 1.8 m to a depth of 8.2 m, characterized by particularly low strength parameters and low deformation parameters. Organic and mineral soils found in the embankment base should be classified as soft soils. The groundwater level is approximately 0.6 m below the embankment's base (Figure 2c).

To assess the construction of the embankment, the electrical resistivity tomography (ERT) tests were also conducted, which show its cross-sectional structure. The results of geophysical measurements are presented in Figure 3. Analyzing these studies, we can conclude that the body of the embankment consists of noncohesive soils (sands) and the structure of the embankment is homogeneous, without visible soil lenses. Zones with increased electrical resistivity in the upper layer result from the presence of a breakstone layer, while zones with low electrical resistivity at the base of the embankment are due to the presence of water in the residual soils and the presence of organic or clayey materials.

The geoelectric cross section in conjunction with the material index I_D from DMT at the classification chart (Fig. 4) allows to conclude that sandy soils with occasional presence of silty (clayey) and organic soils at the base of the embankment are present throughout the entire profile.

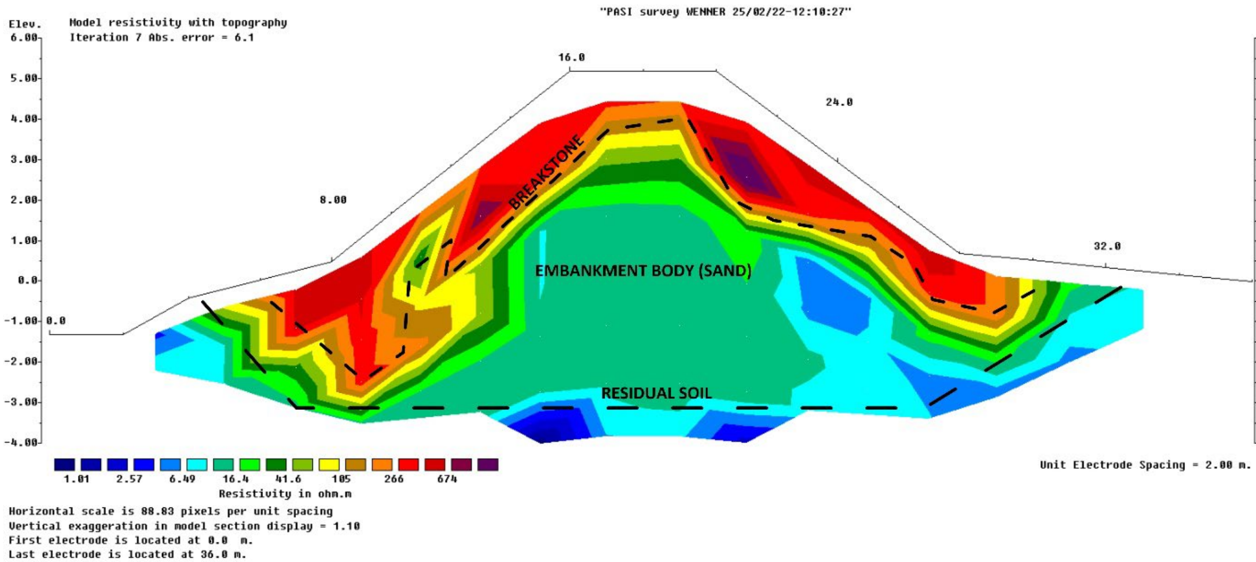

Figure 3: Geoelectrical cross section across the railway fill.

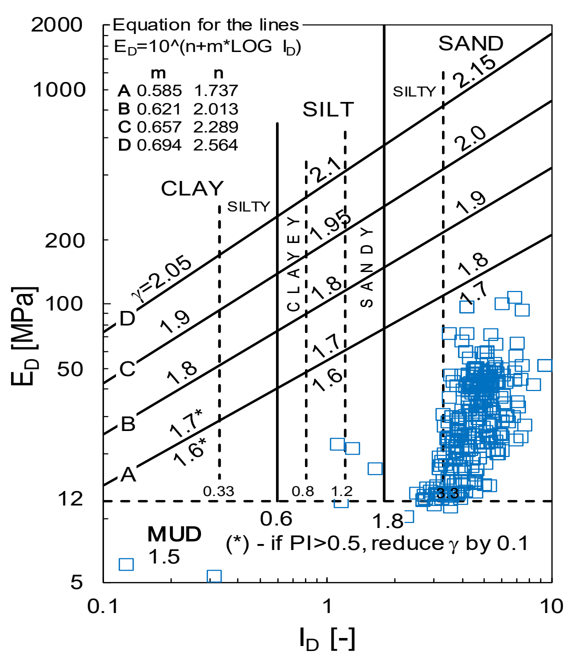

Figure 4: Soil classification chart by DMT.

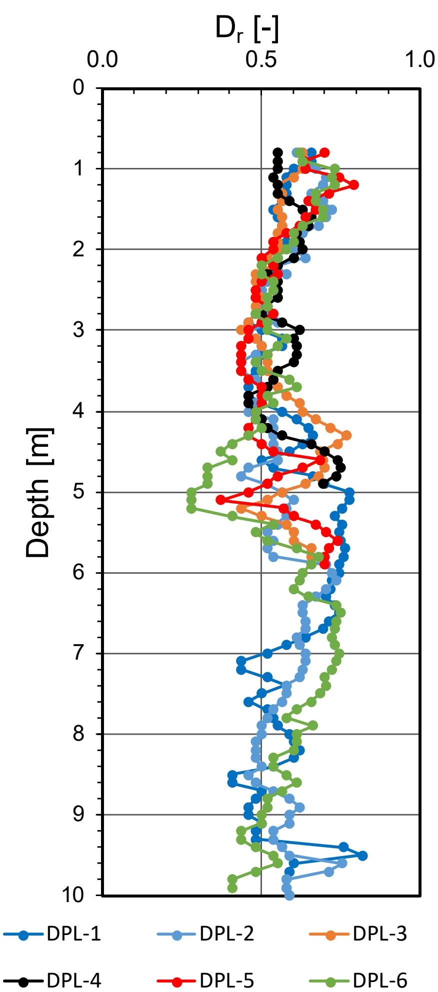

Figure 5: Relative density of sands based on DPL tests.

3 Results and Discussion

3.1 Results of DPL testing and DMT

From the results of the DPL tests (Fig. 5), it can be stated that both the embankment and the subsoil beneath the embankment exhibit a medium-dense condition throughout the entire profile. From the ground surface (or more precisely, from 1 m, as the *in situ* test results

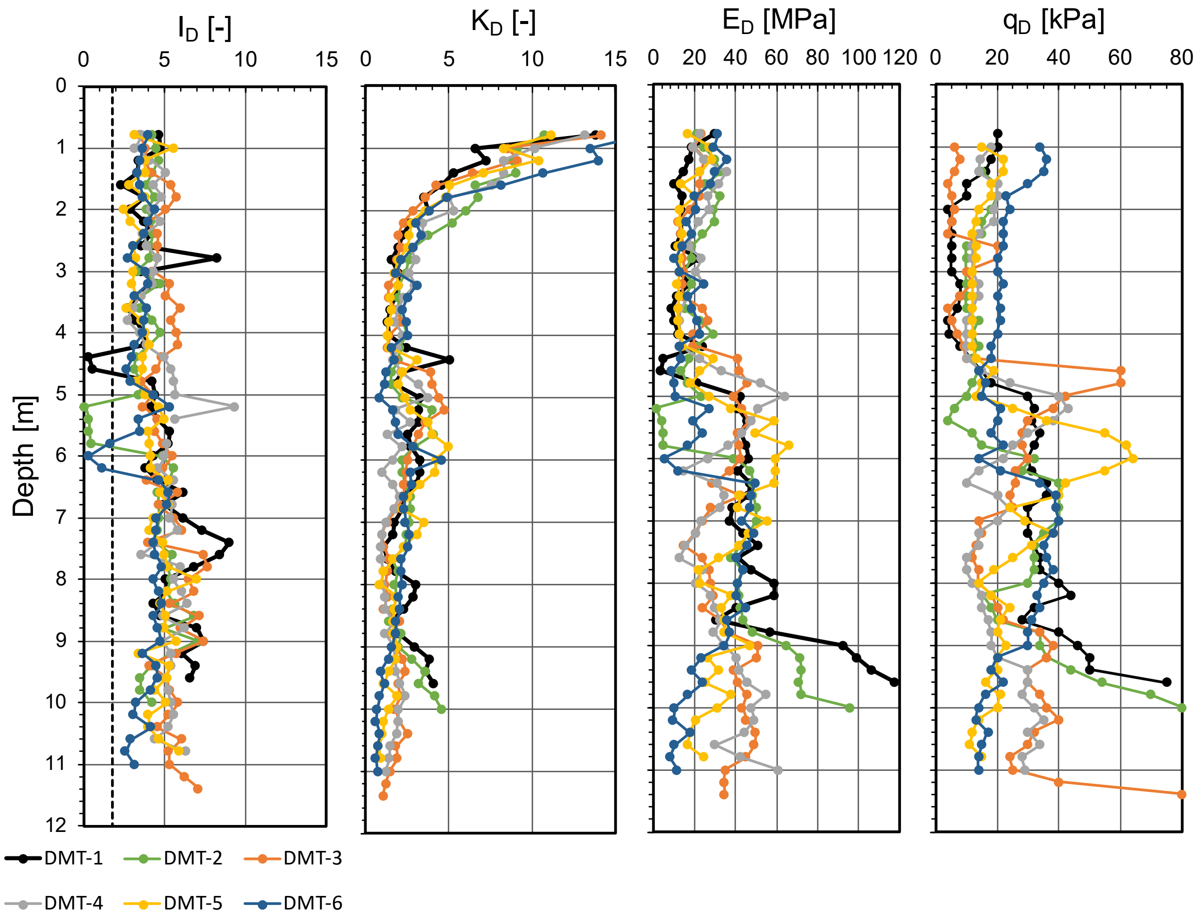

Figure 6: DMT results.

are analyzed from this depth), up to approximately 1.5 m deep, the relative density of the embankment exceeds the value of 0.65 and even reaches 0.8. The embankment's loose zone, where the relative density falls below the value of 0.35, occurs from a depth of 3.2 m and depends on the cross section where the test was conducted. Profile 6 is an exception, where the embankment's loose zone and dry density fall below the value of 0.35 at a depth of approximately 4.4 m. These results provide a background for the values of this parameter according to the newly proposed relationship.

Figure 6 shows the results of DMT in the form of profiles of DMT index changes. The change in the material index I_D confirms that the soils are noncohesive. An exception is observed in DMT-1, DMT-2, and DMT-6, where lenses of cohesive soils are found – the index value drops below 1.8.

Horizontal stress index (K_D), according to what Larsson observed (1989), assumes significantly higher values up to a depth of 2 m (in our case, 2.4 m) than deeper in the profile. Since most formulas in the literature base the value of relative density precisely on the K_D index, this results in a significant overestimation of soil compaction in this layer.

The analysis of changes in the soil profile of the K_D and E_D indices, as well as wedge resistance – q_D – does not allow for direct conclusions about the relative density of the investigated soils.

3.2 Estimation of relative density based on DMT

The dilatometer indices (I_D, K_D, E_D), wedge resistance (q_D), pressures (p_0 and p_1), and vertical effective stress ($'_{v0}$) were investigated to estimate their influence on the relative density of the embankment. For the statistical analysis, measurement results from DMT-1, -2, and -3 were used, that is, data from 107 depths. The table shows Pearson product moment correlations between each pair of variables. These correlation coefficients range between –1 and +1 and measure the strength of the linear relationship between

Table 1: Correlation coefficient matrix for various soil parameters.

	D_r	p_0	p_1	I_D	K_D	E_D	q_D	’$_{v0}$
D_r		0.392 0.000	0.379 0.000	0.053 0.491	0.740 0.000	0.499 0.000	0.526 0.000	0.11 0.140
p_0	0.392 0.000		0.951 0.000	0.139 0.069	0.156 0.042	0.816 0.000	0.322 0.000	0.535 0.000
p_1	0.379 0.000	0.951 0.000		0.412 0.000	0.106 0.168	0.888 0.000	0.547 0.000	0.593 0.000
I_D	0.053 0.491	0.139 0.069	0.412 0.000		0.12 0.127	0.394 0.000	0.178 0.000	0.343 0.000
K_D	0.740 0.000	0.156 0.042	0.106 0.168	0.12 0.127		0.264 0.001	0.328 0.000	0.40 0.000
E_D	0.499 0.000	0.816 0.000	0,888 0,000	0.394 0.000	0.264 0.001		0.771 0.000	0.569 0.000
q_D	0.526 0.000	0.322 0.000	0,547 0,000	0.178 0.000	0.328 0.000	0.771 0.000		0.355 0.000
’$_{v0}$	0.11 0.140	0.535 0.000	0.593 0.000	0.343 0.000	0.40 0.000	0.569 0.000	0.355 0.000	

the variables. The second number in each location of the table is a *P*-value, which tests the statistical significance of the estimated correlations. *P*-values below 0.05 indicate statistically significant nonzero correlations at the 95% confidence level.

As indicated by the above analysis, the highest correlation of 0.74 was found between relative density and horizontal stress index. Relative density also depends, in sequence, on wedge resistance, dilatometer modulus, and pressures p_0 and p_1, but it does not depend on the material index and vertical effective stress.

Considering the above, using the solver module, an equation has been proposed to determine density based on calculated dilatometer indices. This equation takes the following form:

$$D_r = \ln\left(\frac{0.1 \cdot K_D \cdot E_D}{P_a}\right)^{0.125} \quad (10)$$

where: D_r is the relative density (-), K_D the horizontal stress index (-), E_D the dilatometer modulus (MPa), and P_a is the atmospheric pressure (MPa).

The relationship between the analyzed data on the plane described by the proposed formula is shown in Figure 7a, while the relationship between the reference data from DPL tests and the predicted one is shown in Figure 7b. In accordance with the diagram, the agreement between the parameter calculated based on DMT and the parameter obtained from DPL results is high (coefficient of determination R^2 = 0.691, mean square relative

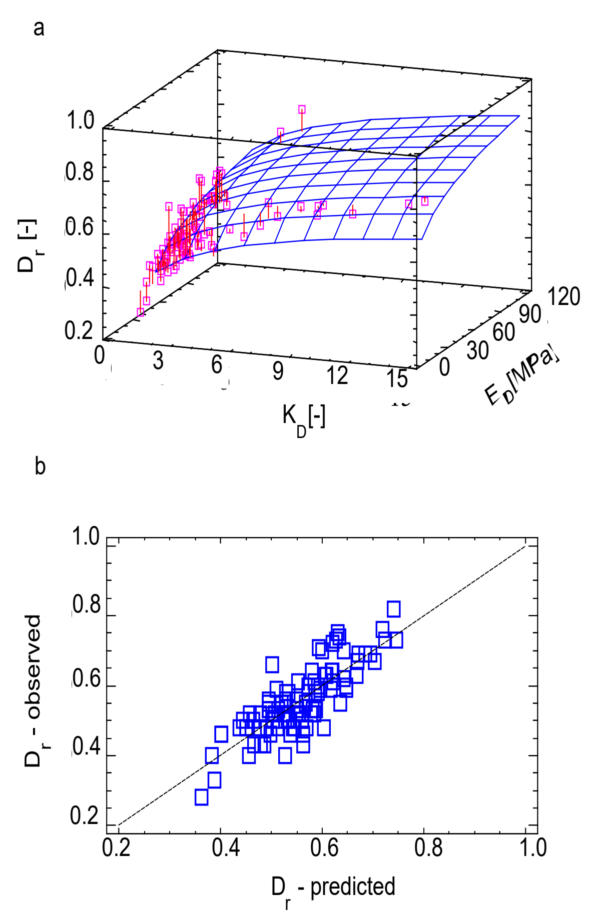

Figure 7: Plot of $D_r = f(K_D, E_D)$ relationship (a) and predicted versus obtained data on the investigated area.

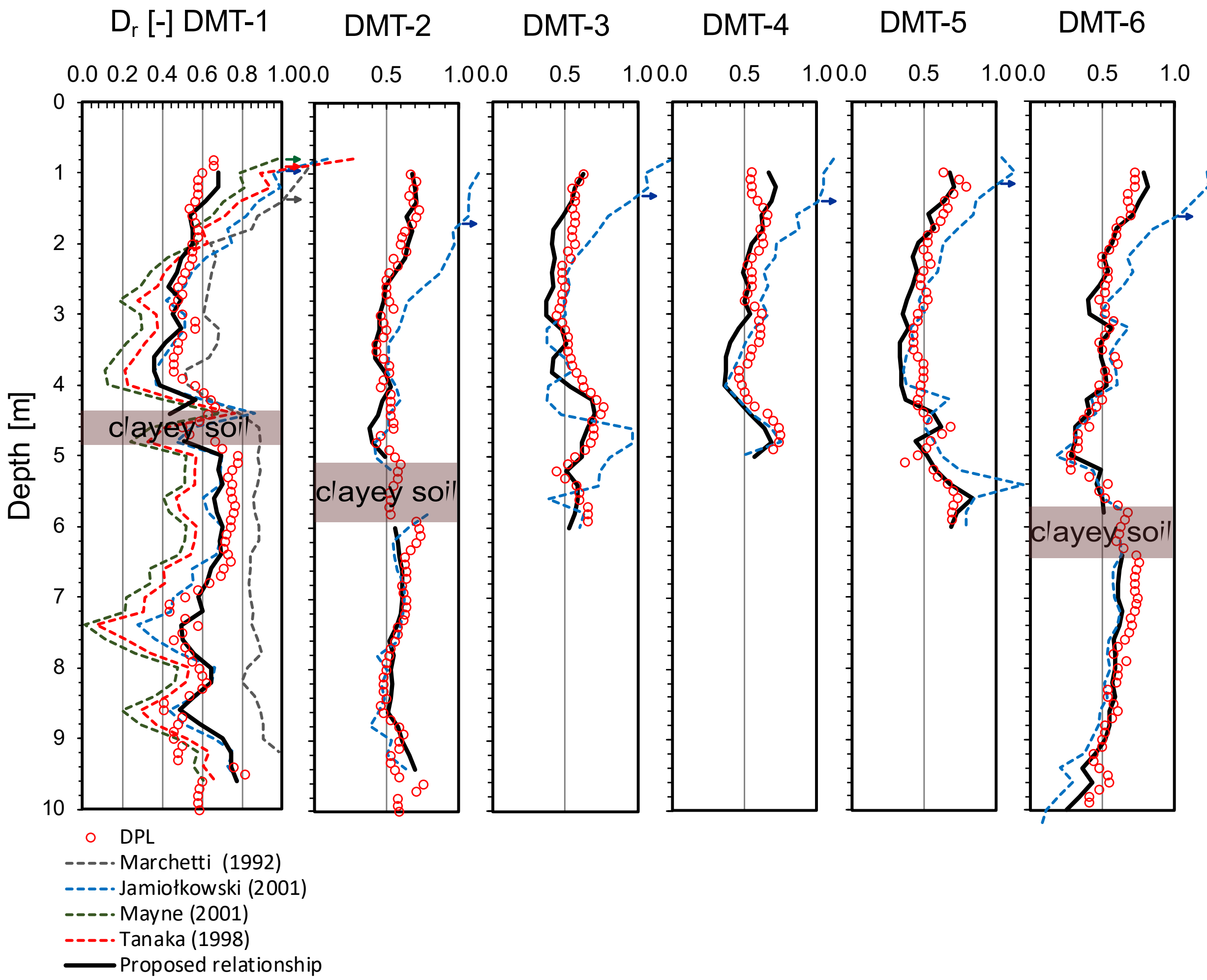

Figure 8: Relative density (D_r) estimated based on the proposed formula (Eq. 10) versus values determined from DPL tests and calculated from literature-based relationships.

displacement [MSRD] = 12.7%, and mean relative error [MRE] = 8.8%).

In Figure 8, the results of relative density are presented according to the new formula proposed in the paper. The relative density is compared against values determined in the field using DPL soundings (these represent reference values) and those calculated based on DMT using the relationships provided in the literature. The first formula for assessing D_r is the Marchetti correlation, which relates it to the wedge resistance (q_D). Here, soil relative density is clearly overestimated not only compared to DPL test, but also compared to other methods – all relationships mentioned in the article were plotted only for the DMT-1 profile (other profiles present only data obtained from DPL, calculated according to the Jamiolkowski formula and according to the proposed one).

On analyzing the relationships proposed by Tanaka (1988), Mayne (2002), and Jamiolkowski et al. (2001), it is found that despite differences in formula forms, the shapes of the graphs are almost identical with a slight shift – this is well illustrated by the results from DMT-1.

In all cases (Eqs 1–4), it is evident that the density is significantly overestimated in the first few meters of the profile, and it is almost a rule that it exceeds the value of 1 up to a depth of 2 m. With increasing depth, density values decrease, and in the case of the proposal provided by Tanaka and Mayne, they underestimate relative density. The D_r values closest to the reference ones are given by the Jamiolkowski correlation.

The change in relative density in the profile according to the newly proposed correlation depends not only on horizontal stress index, but also on dilatometer modulus. It can be observed that the estimated values in this case are closest to DPL values. Moreover, there is no overestimation of density in the first meters of the profile. Measurements from DMT-4, -5, and -6 were not considered in the statistical analysis, and data from these studies were not used in the search for dependencies between relative density and DMT indices, so they serve as a kind of verification of the proposed correlation.

It should be noted that, as with the other relationships mentioned in the article, the one proposed now has a local character and will require further verification and adjustment of the constants present in the equation.

4 Conclusion

Based on the literature review and analysis of results using the relationships proposed by Marchetti (1980), Tanaka and Tanaka (1998), Jamiolkowski et al. (2001), as well as Mayne (2002), it can be concluded that the fill density exhibits significant differences depending on the applied calculation method. The best fit among the literature-based relationships and reference data is the formula proposed by Jamiolkowski et al. (2001) and in our conditions, it can be successfully used for the preliminary assessment of relative density. Its advantage is further supported by the fact that it is commonly used and partially verified.

Statistical analysis confirmed previous studies and indicates that relative density correlates best with horizontal stress index (K_D), wedge resistance (q_D), and dilatometer modulus (E_D) in the same order. However, the authors chose to use K_D and E_D in the newly proposed formula because q_D is not always measured in the field. In addition, during these studies, a friction reducer was used, and it is challenging to predict the results of statistical analysis in other scenarios (e.g., absence of a friction reducer, stratification of cohesive soils, etc.). It is also important to note the strong correlation between wedge resistance and dilatometer modulus, as reflected in the numbers in Table 1 (the relationship between these variables is even highlighted, and further research may consider taking advantage of this fact).

The proposed relationship for relative density assessment provides a good match with the results of DPL tests. It is of a local nature, and due to the limited amount of data, it requires further verification. It might be possible to further refine the calculation outcomes to closely align with the DPL tests, but it is preferable for the proposed correlation to slightly underestimate rather than overestimate the results, making it a more cautious approach. The proposed relationship is worth considering, as it eliminates errors in the near-surface sounding zone. A significant improvement over the literature-based relationships, it yields good results even in the upper profile, accurately reflecting soil compaction in that zone. Further research should be undertaken to verify the suitability of DMT for investigating the relative density of noncohesive soils in Poland and beyond.

References

[1] Borowczyk, M., & Frankowski, Z. B. (1981). Dynamic and static sounding results interpretation. *Soil Mechanics and Foundation Engineering. Proc. 10th International Conference, Stockholm, June 1981. Vol. 2, (A.A. Balkema)*.

[2] EN1997-2:2007. Eurocode 7. Geotechnical design - Part 2: Ground investigation and testing. CEN, Brussels.

[3] Gruchot, A. (2019). Assessment of soil compaction and shear strength of the side dam of the Maziarnia water reservoir. *Acta Scientiarum Polonorum Formatio Circumiectus, 18(3),* 133–147. https://doi.org/10.15576/asp.fc/2019.18.3.133

[4] Hawrysz, M., & Stróżyk, J. (2015). The controversial interpretation of dynamic probing results in engineering practice. *Inżynieria Morska i Geotechnika, 3,* 203–207. (in Polish)

[5] Jamiolkowski, M., Leroueil, S., & lo Presti, D.C.F. (1991). Design parameters from theory to practice. *Proceedings of the International Conference on Geotechnical Engineering for Coastal Development, Yokohama, Japan.*

[6] Jamiolkowski, M., lo Presti, D. C. F., & Manassero, M. (2003). *Evaluation of Relative Density and Shear Strength of Sands from CPT and DMT*. https://doi.org/10.1061/40659(2003)7

[7] Jamiolkowski, M., lo Presti, D.C.F., & Manassero, M. (2001). Evaluation of relative density and shear strength of sands from cone penetration test (CPT) and flat dilatometer test (DMT). *ASCE Geotechnical Special Publication No. 119*, 201–238.

[8] Koda, E., Tkaczyk, A., Lech, M., & Osiński, P. (2017). Application of Electrical Resistivity Data Sets for the Evaluation of the Pollution Concentration Level within Landfill Subsoil. *Applied Sciences, 7(3):262,* https://doi.org/10.3390/app7030262

[9] Larsson, R. (1989). The dilatometer test for assessing soil layer sequences and properties in the ground. *Swedish Geotechnical Institute, Linköping, Information No. 10*. (in Swedish)

[10] Lech, M., Skutnik, Z., Bajda, M., & Markowska-Lech, K. (2020). Applications of Electrical Resistivity Surveys in Solving Selected Geotechnical and Environmental Problems. *Applied Sciences*. 2020; 10(7):2263. https://doi.org/10.3390/app10072263

[11] Marchetti, S. (1980). In Situ Tests by Flat Dilatometer. *J. Geotech. Geoenviron. Eng*, *106*, 299–321.

[12] Marchetti, S. (1992). The Flat Dilatometer Test. *U.S. Department of Transportation Federal Highway Administration Publication No FHWA-SA-91-044*.

[13] Marchetti, S., & Monaco, P. a. V. (2018). Recent improvements in the use, interpretation, and applications of DMT and SDMT in practice. *Geotechnical Testing Journal*, *41*(5) https://doi.org/10.1520/gtj2017038

[14] Mayne, P. W., Christopher, B. R., & DeJong, J. (2002). Subsurface Investigations — Geotechnical Site Characterization

Reference Manual. *U.S. Department of Transportation Federal Highway Administration NHI Course No. 132031*, *132031*.
[15] Meardi, G. (1971). Discussion: The Correlation of Cone Size in the Dynamic Cone Penetration Test with the Standard Penetration Test. *Geotechnique, 21*, 184-190.
[16] Młynarek, Z. (2013). Session report: Direct push-in in situ test. *Geotechnical and Geophysical Site Characterization 4 - Proceedings of the 4th International Conference on Site Characterization 4, ISC-4*, *1*.
[17] Młynarek, Z., Wierzbicki, J., & Wołyński W. (2018). Use of functional cluster analysis of CPTU data for assessment of a subsoil rigidity. *Studia Geotechnica et Mechanica*, 40(2): 117-124. https://doi.org/10.2478/sgem-2018-0017
[18] Młynarek,Z., Wierzbicki,J., & Lunne,T. (2021). Usefulness of the CPTU method in evaluating shear modulus G_0 changes in the subsoil. *Studia Geotechnica et Mechanica*, *43(3)* 195-205. https://doi.org/10.2478/sgem-2021-0008
[19] Nepelski, K. (2020). Interpretation of CPT and SDMT tests for Lublin loess soils exemplified by Cyprysowa research site. *Budownictwo i Architektura, 18(3)* 063–072. https://doi.org/10.35784/bud-arch.890.
[20] Pinheiro, C., Molina-Gómez, F., Rios, S., Viana da Fonseca, A., & Miranda, T. (2018). Correlations between Dynamic Penetrometer Light and Cone Penetration Tests in Intermediate Soils: a Statistical Comparison. *XIX Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica Geotecnia e Desenvolvimento Urbano COBRAMSEG 2018, Brasil,* 1-9.
[21] PN-B-04452:2002. Geotechnics. In situ investigations. Polski Komitet Normalizacyjny, Warsaw. (in Polish).
[22] Rabarijoely S. (2018). A New Approach to the Determination of Mineral and Organic Soil Types Based on Dilatometer Tests (DMT). *Applied Sciences* 8(11):2249. https://doi.org/10.3390/app8112249
[23] Rabarijoely, S., Lech, M., & Bajda, M. (2021). Determination of Relative Density and Degree of Saturation in Mineral Soils Based on In Situ Tests. *Materials (Basel, Switzerland)*, *14*(22), 6963. https://doi.org/10.3390/ma14226963
[24] Reynolds, J.M. (2011). An introduction to applied and environmental geophysics. John Wiley and Sons Ltd. New 437 York.
[25] Tanaka, H., & Tanaka, M. (1998). Characterization of sandy soils using CPT and DMT. *Soils and Foundations*, *38*(3). https://doi.org/10.3208/sandf.38.3_55
[26] Tarnawski M. (2010). The need for verification of the interpretation of dynamic tests. *Inżynieria Morska i Geotechnika, 31(3),* 441–443. (in Polish)
[27] Totani, G., Marchetti, S., Monaco, P., & Calabrese, M. (2001). Use of the Flat Dilatometer Test (DMT) in geotechnical design. I*ntnl. Conf. On In situ Measurement of Soil Properties, Bali, Indonesia,* 1-6.
[28] Ura, M., & Tarnawski, M. (2014). Interpretation of relative density of non-cohesive soils on the grounds of static and dynamic penetrometer results. *Przegląd geologiczny*, *62(10/2)*, 715-720 (in Polish).
[29] Virsis, E., Paeglitis, A., & Jateikienė, L. (2023). Analysis of Physical and Mechanical Soil Properties Determined Using Interpretations of Dilatometer Test (DMT) and Cone Penetration Test (CPT) Methods. *The Baltic Journal of Road and Bridge Engineering 18(2)* https://doi.org/10.7250/bjrbe.2023-18.605