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ASSESSMENT OF THE DETERMINED GROUND COMPACTION OF ANTHROPOGENIC SOIL CONTAINING HARD COAL MINE WASTE USING THE DPSH DYNAMIC PROBE

The shortage of investment areas may be at least partially satisfied by the development of reclaimed post-mining areas. These are often subsidence zones levelled with hard coal mine waste or reclaimed sub-level old dumps of this waste. From the geotechnical point of view, such grounds represent anthropogenic grounds containing mine waste, and they are considered as possessing unfavourable properties in terms of the foundation of building structures. The paper initially presents the analysis of the properties of waste from the hard coal mining industry, emphasising that they expose several beneficial properties enabling their safe use. The second part of the article is devoted to the determination of soil density using the DPSH probe. It has been found that the applicable standards lack complex relationships that would allow for a reliable interpretation of the measurement results in a wide range of soil types. The last part presents exemplary results of measurements made with the DPSH probe at a construction site. The obtained results allowed for the formulation of several conclusions regarding the possibility of building on a ground made of hard coal waste and the use of dynamic sounding to assess the geotechnical properties of such anthropogenic soil.

Keywords: anthropogenic soils/ground; dynamic probing; hard coal mine waste; made grounds; post-mining land reclamation

Notation

a_1 – coefficient dependent on the type of soil and the presence of groundwater
a_2 – coefficient dependent on the type of the probe
C_u – coefficient of grain size uniformity
$e_{\max}$ – the maximum porosity index (at the loosest grain arrangement)
$e_{\min}$ – the minimum porosity index (at the densest grain arrangement)

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e	–	in-situ porosity index
I_D	–	(soil) density index
I_S	–	soil compaction index
I_L	–	liquidity index
I_{SR}	–	required value of the soil compaction index
k	–	penetration length of a dynamic probe penetration
N_{DPSH}	–	number of strokes per 20 cm penetration length of a DPSH probe
N_{SPT}	–	number of strokes per 10 cm penetration length of a SPT probe
q_s	–	cone penetration resistance, MPa
w_{opt}	–	optimum moisture content
ρ_d	–	in-situ dry density
$\rho_{d\max}$	–	maximum dry density (at the densest arrangement of the grains)
$\rho_{d\min}$	–	minimum dry density (at the loosest arrangement of the grains)
ρ_{ds}	–	maximum dry density by optimum moisture content (w_{opt})

1. Introduction

In the Upper Silesia Coal Basin (USCB), according to various estimates, between 700 million to 1000 million tons of hard coal waste has been accumulated [1]. Depending on the mining and geological conditions prevailing locally in a given part of a coal seam, waste constitutes between 20% to 50% of the extracted mineral. In 2019 only 61.8 million tons of hard coal was mined (the extraction of this raw material has been decreasing every year since the 1970s and 1980s when it reached nearly 200 million tons per year), the mass of generated waste can be estimated at around 25 million tons (Environment 2019). As a consequence, in the USCB area, there are ca. 220 coal-mining waste dumps covering a surface of over 4000 ha [2-3].

Since the 1980s, environmental protection requirements and, above all, the introduction of fees for waste disposal, prompted the mines to abandon landfilling and maximise the use of waste on the ground [3]. In 2018, data shows that 27.3 million tons of hard coal waste, categorised as rock mass, was properly handled [4].

Fields of the utilisation of mine waste should be analysed from the point of view of contamination and potential qualification as hazardous waste sites [5]. There are no restrictions on the release of waste from Carboniferous strata into the environment, with some restrictions on the concentrations of selected elements and chemical compounds in the aqueous leachates [6-7].

Also, the works are carried out to eliminate or re-shape them in a way that is more acceptable for the landscape, possibilities of their use, and public safety. The current mining operations and liquidation of old spoil heaps create the need to constantly find the methods of their effective management in large quantities and with the shortest possible routes of transport.

In the conditions of a highly urbanised Upper Silesian agglomeration, in which there are significant areas of valuable land classified for various reasons as brownfields [8], there is a need to adapt land with relatively unfavourable geotechnical properties for investment purposes. Brownfields are subject to revitalisation in various directions, but the most valuable of them is the acquisition of land for development and industrial investments.

From the geotechnical point of view, managed mining waste is a kind of anthropogenic soil from which various earth structures are made, such as road and railway embankments, flood defences, elements of landfill constructions, and others [9].

Under the conditions of the USCB, an important sphere of rock mass management is land levelling, i.e. liquidation of subsidence troughs, depressions, and sinkholes resulting from underground mining activities [10]. In many cases, the restoration of the original height of the land surface by filling them with rock masses is necessary to maintain the appropriate levels of groundwater or flow directions of surface watercourses [9]. According to the classification of anthropogenic grounds [11], the rock masses are used for earthworks in the made grounds and as fill material in the reclamation of worked and infilled grounds, mainly in post-mining areas, as shown in Fig. 1.

Fig. 1a. Typical forms of final utiliation of waste – reclaimed landfill

Fig. 1b. Typical forms of final utiliation of waste – waste managed for levelling a degraded area

In areas reclaimed with the use of hard coal waste, anthropogenic ground layers often create the foundation for buildings and infrastructural objects. Such soils cause problems with foundation construction. These problems result mainly from the wide range of grain size fractions (non-uniformity of soils), variable origin and mechanical properties of rocks forming the soils, and lack of control of the density state during construction works [12]. On the other hand, such soils exhibit advantageous features, namely susceptibility to densification. Hence, it is important to assess the geotechnical properties of this type of anthropocentric land in terms of suitability for the foundation of building structures.

Thus, the soil that is supposed to safely transmit the load caused by the foundation in the future, must fulfil the conditions required by the designer of the structure. These mainly include the proper load-bearing capacity and rigidity that allows the fulfilment of the I and II boundary condition. Both parameters have an impact on the selection of proper foundations for building constructions [13-15].

Due to the extreme non-uniformity of anthropogenic grounds made with hard coal mining waste and a need for deep geotechnical investigation, the only proper method of the field investigation of grounds is dynamic probing using super-heavy (DPSH) standard equipment [16]. However, The main method of soil investigation used around the world is the cone penetration test (CPT), for which a large theoretic base has been developed for years [17]. This approach is reflected by valid standard Eurocode 7 [18], according to which the main calculation method for pile-bearing capacity is based on the results of CPT testing.

The paper presents the results of dynamic probing tests with the use of a super heavy dynamic penetrometer, which was conducted in anthropogenic soils containing hard coal waste to determine the loading of the soil for the designed construction works.

2. Characteristics of hard coal mine waste

Storage and beneficial use of waste should be analysed from the point of view of contamination and potential qualification as a hazardous waste site [5].

The anthropogenic soil obtained from hard rock coal waste is an atypical coarse-crumb rock material characterised by the features of both coarse-grained and fine-grained soils.

Coal waste from hard coal mines contains in their petrographic composition claystones and clayey shales (31% ÷ 98%), mudstones (2% ÷ 47%), sandstones (0% ÷ 33%), and in some regions also conglomerates and carbonates. Coal waste may also contain 2% ÷ 25% of combustible coal shales, which may contain up to 30% of the carbonaceous matter and hard coal residues in the amount from 3% to even 10%. The mineral composition includes clayey minerals (43% ÷ 54%), quartz (10% ÷ 13%), and 10% ÷ 20% other minerals and carbonaceous matter [2,19].

Hard coal waste stored on the ground surface exposed to the influence of atmospheric factors (oxygen, water, and temperature fluctuations) is subject to intense physical and chemical weathering processes, which significantly change their structure and properties. Therefore hard coal waste is divided into [15]:

Fresh waste (from current production and stored up to 0.5 year),
- Relatively fresh) 0.5 ÷ 1.0 years),
- Partially weathered (3 ÷ 15 years),
- Fully weathered (older than 15 years).

Factors causing physical airing include insolation, water freezing and thawing, swelling of clay minerals, osmotic action of salt, water and air penetration into cracks and pores. Chemical weathering is influenced by the dissolution of mineral substances, hydration, hydrolysis, carbonation and oxidation, the extreme manifestation of which is dump fires, which result in the thermal transformation of hard coal waste. In thermally transformed waste, claystones and mudstones acquire properties similar to clinker due to the decay of kaolinite. During the decomposition of siderite, hematite and maghemite are formed, which gives the thermally transformed waste a brick-red colour. Thermal transformation of hard coal waste leads to significant diversification of their physical and chemical properties, therefore this waste may be divided into burnt and unburnt [20].

The physical and chemical properties of burnt coal waste are so favourable that after their extraction from dumping grounds and fractionation, they are successfully traded as aggregates for constructing roads and trackways that meet the relevant specifications [21]. Table 1 summarises the average values of selected geotechnical parameters of coal waste from hard coal generated in USCB mines. Data contained in Table 1 are the results of the literature research.

TABLE 1

Average values of geotechnical parameters of hard coal waste from USCB mines

Parameter	Symbol	Unit	Fresh waste	Partially weathered waste	Fully weathered waste
Fraction contents					
– Boulder and cobble	f_{bc}	[%]	25-66	30-38	4-18
– Gravel	f_g		30-62	43-54	39-61
– Sand	f_s		2-10	10-15	9-21
– Silt and clay	f_{sc}		2-4	3-8	2-30
Soil heterogeneity index	U	[-]	4-160	22-170	14-270
Mass loss on ignition	I_z	[%]	17-34	17-29	15-27
Moisture	M	[%]	4-13	4-10	5-19
Optimum moisture	M_{opt}	[%]	7-12	9-16	11-19
Maximum bulk density of the grain skeleton	$r_{d\max}$	[kg/m^3]	1700-1900	1600-1900	1200-2000
Bulk density of the loose grain skeleton	r_{do}	[kg/m^3]	1200-1500	1390-1410	1280-1300
Specific density	r_s	[kg/m^3]	2000-2600	2200-2300	2100-2500
Filtration coefficient for $I_s = 0.95$	k	[m/s]	10^{-4}-10^{-5}	10^{-4}-10^{-6}	10^{-4}-10^{-8}
Internal friction angle for $I_s = 0.95$	F	[°]	38-47	36-42	30-46
Cohesion for $I_s = 0.95$	c	[kPa]	4-35	21-33	10-48

Grain-size composition of hard coal waste

Hard Coal waste contains fractions ranging from rocky to dust-clay, with the proportions of individual fractions changing over time [15,19]. The sample changes in the average particle size distribution of the hard coal waste are illustrated in the diagrams in Figs. 2 and 3. Fig. 2 shows the average particle size distribution of hard coal waste samples collected from the places of their deposition.

Fig. 3 illustrates the effect of water on the particle size distribution of coal wastes tested in laboratory conditions. In the initial period, coarse grains of waste disintegrate, increasing the share of sand and gravel fractions. In the second phase, the gravel phase also undergoes deterioration. In laboratory conditions, the grain disintegration process stabilises after about 20-25 days of soaking the waste, and after this time, no further significant changes in the grain composition are observed, Fig. 3 [22].

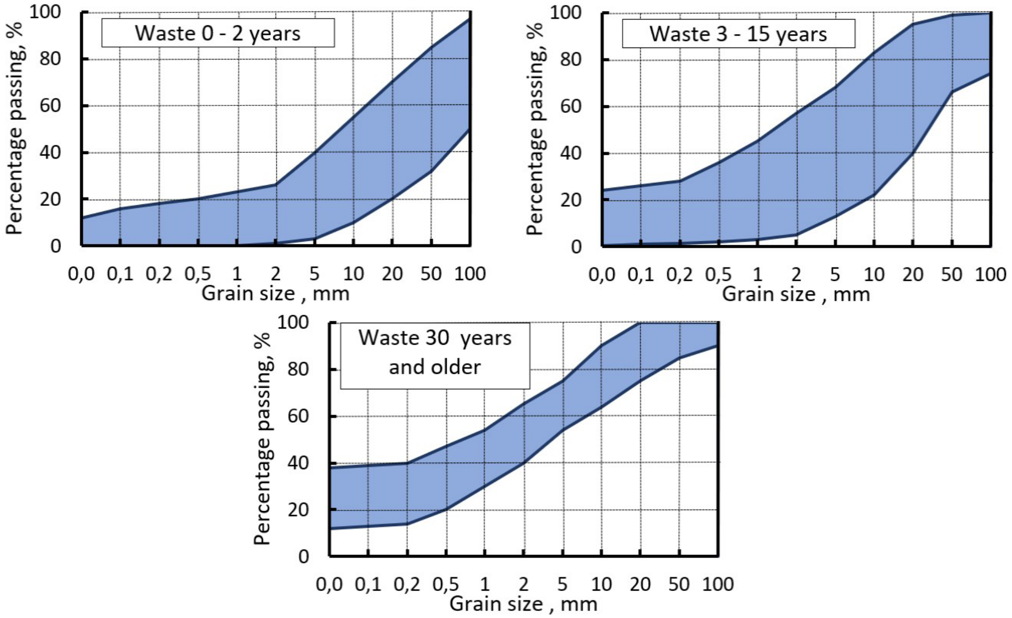


Fig. 2. Average grain-size distribution of hard coal waste from USCB mines in relation to their age

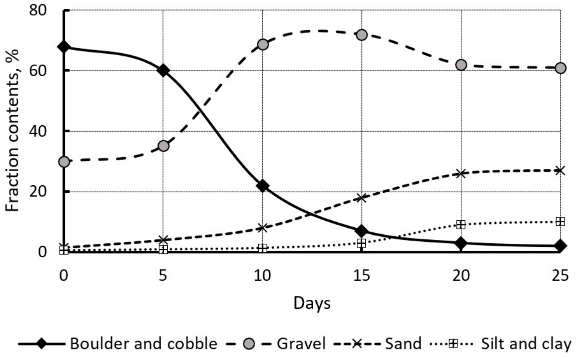


Fig. 3. Decomposition of grain fractions of exemplary fresh hard coal waste as a result of soaking in water

The progressive process of physical weathering of the coarse rock material accumulated in the landfill increases its fragmentation and moisture content, which improves its compaction in earthworks. The progressive fragmentation of the waste may result in excessive growth of fine dust and clay fractions, including the presence of expansive soil properties, which in turn may limit the scope of their use in structures (or places) exposed to water and frost.

Content of other anthropogenic materials in hard coal waste

The hard coal waste from mines may contain small amounts of unsorted waste of various origins, such as rubber bands, pieces of wood, sawdust, fragments of work clothes, cloths soaked in grease and oils, steel scrap, rubble, plastics, cable insulation, hoses and rubber waste, and others. The content of this waste is relatively small, as it does not exceed 0.2% of the total volume of the fill, but there is a potential risk of local clusters [24].

Another frequently occurring problem in old landfills and existing wastelands intended for remediation is the occurrence of uncontrolled accumulations of waste from human activities, mainly in the form of construction debris and household waste [25].

Fire hazard from hard coal waste

Spontaneous ignition hazard exists for fresh, relatively fresh, and partially weathered hard coal waste, approximately up to 3 years old [26]. One of the factors determining the formation of thermal processes is the supply of a sufficiently large amount of oxygen to the interior of the waste block. Such conditions are met by dumps, embankments, heaps, and all over-ground-level structures where the wind causes air to penetrate through the side surfaces of the slopes [27]. The introduced air heats up and generates convective flow towards the upper part of the waste block through the voids between the grains, intensifying the processes of thermal reactions with the carbonaceous matter.

In the case of placing coal waste at the sub-level (subsidence troughs, sinkholes, open pits, etc.), there is practically no fire risk. When used for levelling areas of fresh and relatively fresh waste (up to 3 years), to eliminate the risk of spontaneous ignition, anti-pyrogenic substances can be added to the waste, or the waste could be covered with insulating layers limiting the air supply [28-29].

Chemistry of leachate from coal-mining waste deposited on the ground surface

A wide range of research described in literature has been offered to the chemistry of mine waste from coal mining both in terms of their state of thermal conversion resulting from spontaneous ignition [29] and the progress of chemical weathering processes [15,30].

In the vast majority of studies on the chemistry of mining waste, the prevailing view is that their use as a raw material for earthworks (filling field basins, levelling the ground surface) does not pose environmental hazards in the context of pollution carried by ground and surface waters [7,10,29-31].

3. The assessment of the compaction quality of anthropogenic soils formed from hard coal waste

The quality of compaction of non-cohesive soils may be determined using the soil compaction index (degree of compactness, compression index) – I_S or density index (relative density) – I_D. The compaction index may be obtained from the formula [32]:

$$I_S = \frac{\rho_d}{\rho_{ds}} \times 100\% \geq I_{SR} \tag{1}$$

Where:

ρ_d — in-situ dry density, Mg/m^3,
ρ_{ds} — maximum dry density by optimum moisture content (w_{opt}), Mg/m^3,
I_{SR} — required value of the soil compaction index, %.

The state of compaction of non-cohesive soils is determined based on the density index, which is defined by the formula [33]:

$$I_D = \frac{e_{\max} - e}{e_{\max} - e_{\min}} = \frac{\rho_{d\max}\left(\rho_d - \rho_{d\min}\right)}{\rho_d\left(\rho_{d\max} - \rho_{d\min}\right)} \times 100\% \tag{2}$$

Where:

$e_{\max}$ — the maximum porosity index (at the loosest grain arrangement), ($\rho_{d\min}$),
$e_{\max}$ — the minimum porosity index (at the densest grain arrangement), ($\rho_{d\mathrm{mix}}$),
e — in-situ porosity index (ρ_d),
$\rho_{d\max}$ — maximum dry density (at the densest arrangement of the grains), Mg/m^3,
$\rho_{d\min}$ — minimum dry density (at the loosest arrangement of the grains), Mg/m^3.

Relative density measures the degree of compactness and stability of a stratum. It is an arbitrary character of a non-cohesive substrate. In a real sense, it expresses the ratio of the actual decrease in volume of voids in a soil to the maximum possible decrease in volume of voids, i.e. how far the soil under investigation is capable of further densification beyond its natural state. Its determination is helpful in the compaction of coarse-grained soils and in evaluating the safe bearing capacity of sandy soils [34].

The soil compaction index can be determined in three ways:

Laboratory research method – In the field, soil samples are taken with a cylinder of known volume. The number of samples taken depends on the area of the construction site. The laboratory performs the Proctor test and determines the maximum and natural density of the soil skeleton of the collected samples [33]. The compaction index is determined from the formula (1);

Testing with a dynamic plate (PLT) – A modern method to quickly determine the compaction index. The survey is conducted in the field. The dynamically loaded slab and the help of built-in sensors allow measuring the dynamic modulus of soil deformation on the basis of which it is possible to directly determine the compaction index value;

Dynamic cone penetration test – The anthropogenic soils with significant non-uniformity and the presence of strong soil layers with the use of static soundings (SPT) are impossible. The dynamic penetration tests (DPT) remain irreplaceable. Due to the lack of calculation techniques, receive data is hard to use in further works of geotechnical designing; therefore it is often attempted to relate DPT data with CPT parameters. These links may be direct or indirect, related to particular parameters of soil properties. For this purpose, the indirect link with intermediate relative density index (ID) is the most commonly used (DPT → ID → CPT).

A static cone penetration test cannot be applied in gravelly and stony soils as it is a case of hard rock waste [35]. The presence of coarse grains of hard rocks may lead to the destruction of the piezocone, which is a vulnerable part of the cone penetration test rig [36]. Dynamic probing using a DPSH probe is an alternative method to CPT static probing [17,37-39] when the made ground (anthropogenic soil) contains coarse grains of hard coal waste, construction debris and other substance, which contribute to the structural heterogeneity of the soil. Static tests, like the cone penetration test (CPT), are becoming more popular due to their higher accuracy and repeatability. They also measure sleeve friction and pore pressure in addition to tip resistance, which makes them a preferred choice [40].

4. Dynamic probing of made grounds

Dynamic probing is recommended to be performed primarily to assess the bearing capacity and deformability of coarse-grained non-cohesive soil layers. However, the literature provides several empirical relationships that allow it to be used for measurements in cohesive soils, mainly in homogeneous soils with very fine and fine graining [40-41].

Dynamic sounding is also used to assess [42]:

- Geotechnical parameters of the tested layer,
- Determination of homogeneity or its lack within a layer or the fill,
- Determining the presence of weak or strong layers within the fill,
- Location of the bedrock roof depth,
- Control of the compaction of embankments and fills made of soil material.

The degree of compaction of coarse soil is the general parameter determined in situ during each construction investment. Its value can be assessed by several probing methods.

Probing instruments have different characteristics, and different methods of investigation may be used [43]. Dynamic probing has been divided into four main types [44-45]: DPL – Dynamic Probe (or penetrometer) Light, DPM – Medium, DPH – Heavy, and DPSH – Super Heavy, depending on the mass of the hammer of 10 kg, 30 kg, 50 kg, and 63.5 kg, respectively. The hammer drop height is 70 cm for the DPSH probe and 50 cm for the other types. Blows are counted every 10 cm except DPSH where 20 cm of cone movement is considered. In South Africa, the DPSH blow count is counted over 30 cm and is referred to as an N_{30SB} [40]. Maximum depth of investigation is up to 8 m for DPL, 25 m for DPM and DPH and up to 30 m for DPSH.

With the increase of the maximum grain diameter in the soil and the share of coarse fractions, a heavier hammer should be used. Therefore for coal waste, it is reasonable to use the DPSH probe ended with a standardised conical tip [46].

Based on the DPT method, only soil density index (ID) can be approximated, however, according to the mentioned standard [46], only for soils above groundwater level. More detailed soil investigations using the DPT method require reliable correlation equations between DPT results and various indexes of soil properties or other types of geotechnical probings, i.e. q_c, N_{SPT} etc. [16].

Based on seven data sets from different geological depositional and weathering environments across South Africa (non-cohesive soils), an approximation for equivalent N_{SPT30} value from DPSH test results (N_{30SB}) has been formulated in a form [47]:

$$Equivalent N_{SPT30} = \frac{q_c}{q_d} \tag{3}$$

Where:

$Equivalent\ N_{SPT30}$ — approximated number of SPT blows for 30 cm penetration,
N_{30SB} — number of DPSH blows for 30 cm penetration.

Correlation coefficient obtained for dependence (3) for all considered data equal $R^2 = 0,5$. It may be considered as not very impressive value, but quite satisfactory compared to many other similar correlations presented in the literature. In particular, in the range of the N_{30SB} up to a maximum of about 60, the estimated N_{SPT30} values correlate well with the measurements.

The estimation for calculation of SPT cone resistance q_c on the basis of N_{DPSH} with a very high correlation coefficient $R^2 = 0.97$ was presented for cohesive soils with different grain sizes in the form [16] in a form:

$$q_c = N_{DPSH}\left(0.4686 - 0.1231 \times \ln(h)\right) \tag{4}$$

Where: h – depth of probing.

Static cone penetration resistance q_c can be made dependent on dynamic resistance q_d, which could be derived easily from any DPT data:

$$\alpha = \frac{N_{30SB}}{0.02 \times N_{30SB} + 0.8} \tag{5}$$

According to Czabo and Pietras [48] an approximation with a linear function resulted in average value of correlation coefficient $\alpha = 2.3$ for medium sands and $\alpha = 1.85$ for a solis made from sand and gravel.

Eurocode 7 (part 2, annex G) [18] suggests using the correlation between the number of blows N10H for estimating cone penetration resistance qc. The relation, originally formulated in 1978 [49], could be used directly only for data from DPH (dynamic probe heavy):

$$q_c = f(N_{DPH}) \tag{6}$$

Hence, a N_{20DPSH} equivalent must be obtained from DPH results in the first place.

Spagnoli [50] collects a range of correlations obtained from different DPSH penetrometers with N_{SPT} by different authors:

- Muromachi and Kobayashi, Penetrometer RTRI-Heavy:

$$\frac{N_{30DPSH}}{N_{SPT}} = 1 \tag{7}$$

- Muromachi and Kobayashi (1982), penetrometer DPSH-ISSMFE, gravel, sand with gravel:

$$\frac{N_{30DPSH}}{N_{SPT}} = 1.15 \tag{8}$$

- Tissoni (1987), penetrometer Super Heavy Meardi AG, sandy-silty gravels:

$$\frac{N_{30DPSH}}{N_{SPT}} = 0.6 \tag{9}$$

- Studio Geotecnico Italiano, sand, fine gravels:

$$\frac{N_{30DPSH}}{N_{SPT}} = 0.5 \tag{10}$$

– Heavy German penetrometer SRS, in accordance with DIN 4094-2, coarse soils:

$$\frac{N_{10DPSH}}{N_{SPT}} = 1.4 \tag{11}$$

Interpretation of dynamic sounding in coarse and/or anthropogenic soils for the purposes of ground compaction is mainly based on the assessment of the value of the density index I_D. The results of dynamic probing are usually interpreted in such a way that a given value of the soil density index I_D is attributed to a certain number of hammer strokes N per penetration length k (10 cm, 20 cm, or 30 cm), thus:

$$I_D = f(N_k) \tag{12}$$

Literature [18,51-53] presents following general formula for calculation of I_D:

$$I_D = a_1 + a_2 \log\left(N_k\right) \tag{13}$$

Where:

a_1 — coefficient dependent on the type of soil and the presence of groundwater',
a_2 — coefficient dependent on the type of the probe,
N_k — number of strokes per k centimetres of penetration length.

The shape of the $I_D(N_k)$ function curve only slightly depends on the type of dynamic probe used for soundings. For the DPSH probe, the Polish standard PN-B-04452:2002 shows the values of empirical coefficients $a_1 = 0.196$ and $a_2 = 0.429 \div 0.441$ for the uniformity coefficient of the soil $C_U \leq 3$. This standard has been replaced by Eurocode 7 Part 2 [18], however, in Annex G, only coefficients for DPL and DPH probes are given with limitation to the uniformity coefficient $C_U \leq 3$ (and $C_U \geq 6$ for DPH only).

As a result, the shape of the function $I_D(N_k)$ for different types of probes takes the form of almost parallel straight lines on the logarithmic graph for N_k values in the range from 3 to 60, Fig. 4.

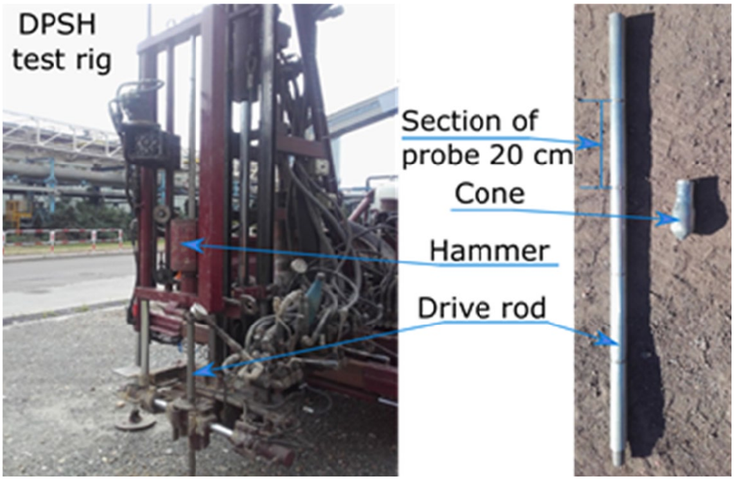


Fig. 4. A general view of the Dynamic Penetration – Super Heavy DPSH

For the assessment of the density index I_D of coarse-grained soils characterised by uniformity coefficient value $C_u > 3$ based on the number of N_{20} strokes for DPSH dynamic probe may be adopted following correlation [53,54]:

$$I_D = 0.196 + 0.441.\log\left(N_{20DPSH}\right) \tag{14}$$

It should be mentioned and added here that probing instruments have different characteristics and different methods of investigation may be used [43]. In the case of dynamic soundings, measurement and interpretation are stepwise every 10 or 20 cm. According to PN-B-04452:2002 [53] (similar division may be found in literature: [43,44]), four types of dynamic probes can be distinguished: DPL – Dynamic Probe (or penetrometer) Light, DPM – Medium, DPH – Heavy, and DPSH – Super Heavy, depending on the mass of the hammer of 10 kg, 30 kg, 50 kg, and 63.5 kg, respectively. The hammer drop height is 70 cm for the DPSH probe and 50 cm for the other types. The kind of dynamic probing is selected following the type of soil tested.

The general view of a DPSH probe is shown in Fig. 5.

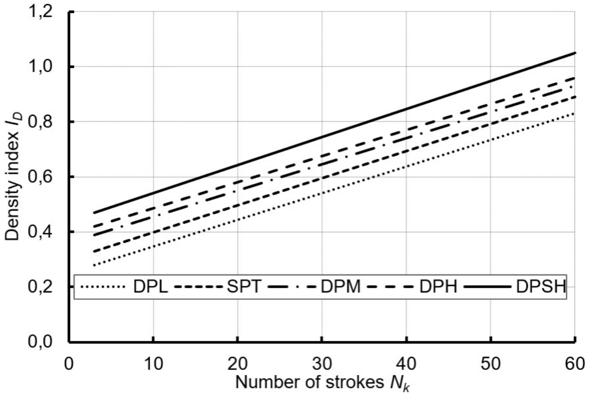


Fig. 5. Density index I_D as a function of number of strokes N_k for different types of dynamic probes accordingly to the PN-B-044522002 standard

5. Description of the case study

The study area was located in the city of Bytom at Kędzierzynska Street (Fig. 6). The main purpose of the research carried out in 2016 was to obtain data on the arrangement of soil layers to determine the geotechnical parameters of the subsoil for possible future construction investments. In order to determine the geotechnical conditions for the foundation of buildings, five small-diameter test boreholes were drilled to a maximum depth of 14 metres. It is mentioned that the number, location and depth of the boreholes were determined and verified on an ongoing basis with the owner of the investment plot in question. These studies were of the nature of preliminary recognition of the prevailing soil and water conditions in the analysed area. During the execution of standard research boreholes ("profile boreholes"), it was found that a significant part of the land lying on the plot is an anthropogenic ground, in which post-mining wastes (waste rock) predominate.

At the stage of making standard test boreholes, it was not possible to specify the characteristic – leading to the geotechnical parameters of these soils.

Therefore, a decision was made to perform additional tests “in the locations” of previously drilled boreholes, where the thickness of anthropogenic grounds was the greatest, with a very heavy dynamic probe (DPSH).

The use of the above-mentioned study was dictated by the fact that the dominant components of the anthropogenic grounds were different fractions of waste rock (claystones, mudstones and sandstones).

Based on our own experience, it was found that during the tests, there would be no risk of damage to the piezoelectric cone of the dynamic probe. The above is justified by the fact that both morphology and lithology (“dimensions” of mining waste) should not cause damage to the probe but may slightly contribute to disturbances/irregularities in measurement readings (probe strokes), as will be shown in the following analysis.

Testing with the DPSH probe in order to determine the degree of compaction of these soils was justified and at this stage of preliminary research, the only right one.

The study of the degree of compaction in these conditions is only an attempt at parameterisation – verification of the obtained assessment results of geotechnical parameters using traditional research boreholes.

Of course, one can argue about the validity of verifying the parameters of anthropogenic grounds, and the need to confirm the density parameter with other dynamic or static probes. But

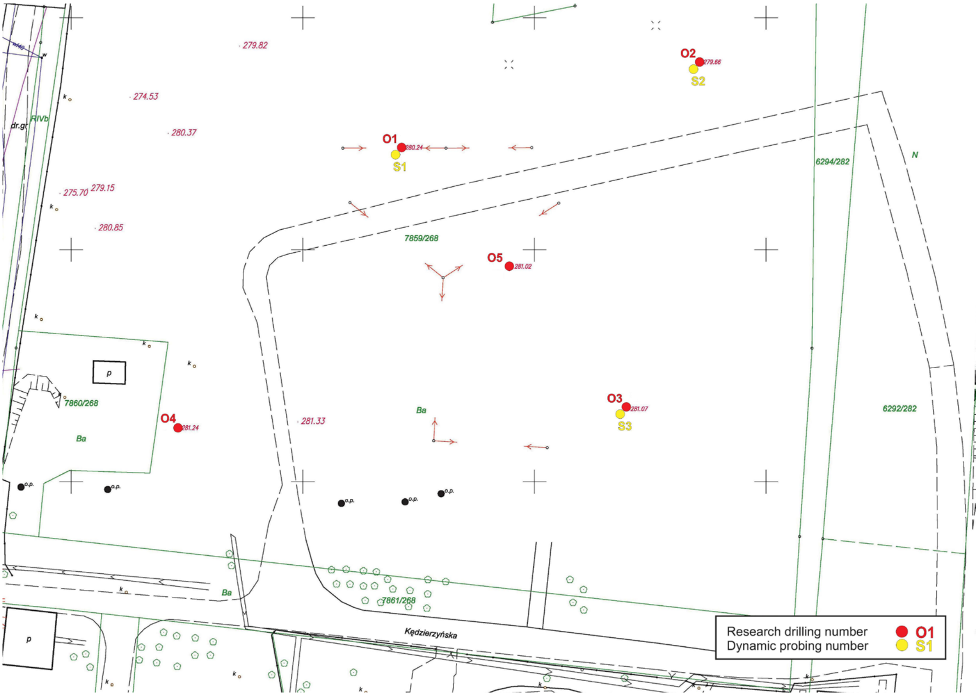


Fig. 6. Site plan with the indication of DPSH probing locations and the locations of the testing boreholes, according to original scale 1500 (author’s work)

as already mentioned, at this stage of the recognition of ground and water conditions in the area in question, the above method was chosen, which the approach does not differ from the standards practised and used by the broadly understood science – geoengineering.

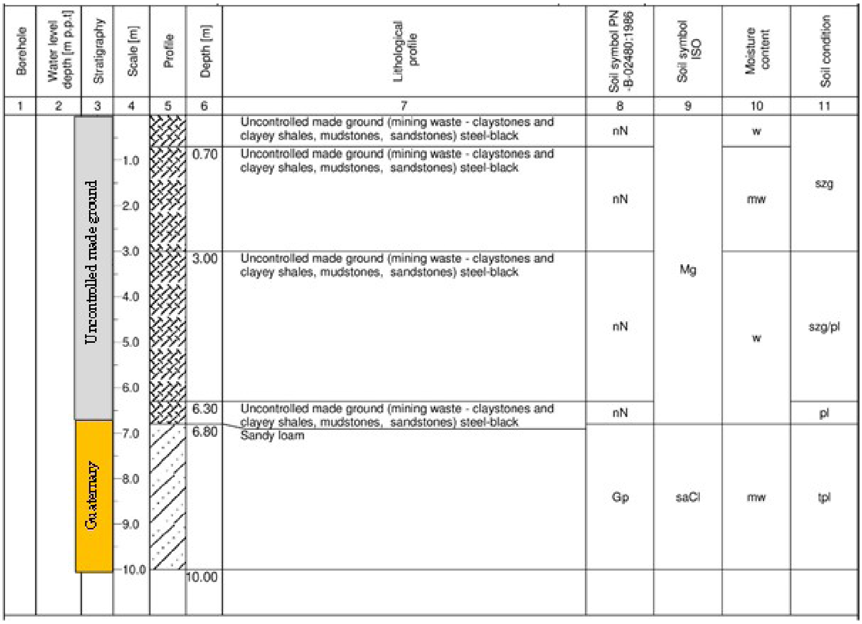
Finally, it was decided to perform three soundings with the DPSH dynamic probe within the test holes 1, 2 and 3 (Fig. 6).

As mentioned, the anthropogenic soil contained mainly claystones and clayey shales, mudstones, sandstones, hard coal mine waste, carbon silt, and to a smaller extent, other industrial waste represented by a mixture of agglomerates, slags, concrete, wood, and dolomite rubble. In its lower part, the made ground was mixed with the native subsoil (Quaternary sediments). After the initial analysis of the profile boreholes, the made grounds have been defined as heterogeneous density layers, from loose up to dense. Examples of research boreholes where dynamic soundings were additionally performed are shown in Figs. 7-9 below.

The Quaternary formations were represented by bearing formations, lithologically classified as sandy silts, silty sand, and silt with a liquidity index $I_L = 0.11\text{-}0.20$ (low-plasticity formations) as well as medium and fine sands with the density index $I_D = 0.45\text{-}0.70$ (medium density soil and dense soils). In terms of the moisture, down to a depth of about 1.0 m, the soil has been determined to be wet, the main mass of the waste was in a slightly wet state, and the Quaternary sands beneath were again wet. The groundwater level was not found in the whole area.

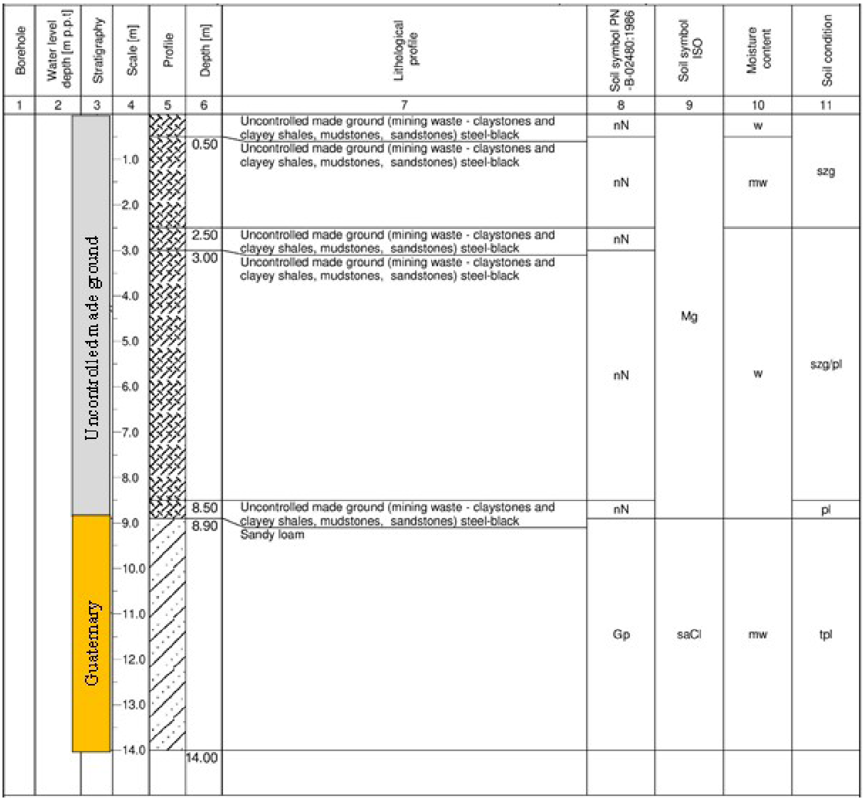
The reference geotechnical parameters, namely the density index I_D (non-cohesive soils) and the plasticity index I_P (cohesive soil) for native grounds have been characterised according to [55] standard and standardised macroscopic assessment of the soil.

As the made ground partially contained non-cohesive soil, its density was estimated initially only approximately (qualitative), without providing a numerical value [56].



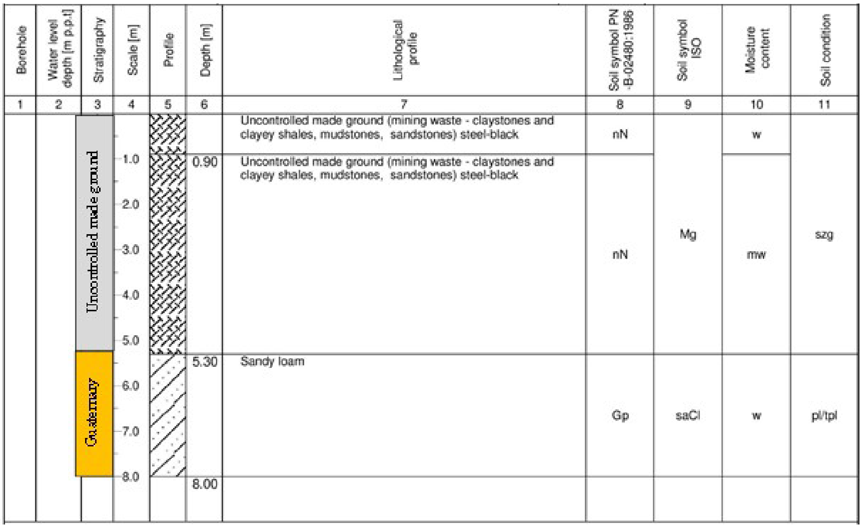
Borehole	Water level depth [m p.p.t]	Stratigraphy	Scale [m]	Profile	Depth [m]	Lithological profile	Soil symbol PN-B-02480:1986	Soil symbol ISO	Moisture content	Soil condition
1	2	3	4	5	6	7	8	9	10	11
		Uncontrolled made ground				Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN	Mg	w	szg
			1.0 2.0		0.70	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN		mw	
			3.0 4.0 5.0 6.0		3.00	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN		w	szg/pl
					6.30	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN			pl
		Quaternary	7.0 8.0 9.0		6.80	Sandy loam	Gp	saCl	mw	tpl
			10.0		10.00					

Fig. 7. Profile of research drill No. 1



Borehole	Water level depth [m p.p.t]	Stratigraphy	Scale [m]	Profile	Depth [m]	Lithological profile	Soil symbol PN -B-02480:1986	Soil symbol ISO	Moisture content	Soil condition
1	2	3	4	5	6	7	8	9	10	11
		Uncontrolled m ade ground				Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN	Mg	w	szg
					0.50	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN		mw	
					2.50	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN		w	szg/pl
					3.00	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN			
					8.50	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN			pl
		Guaternary			8.90	Sandy loam	Gp	saCl	mw	tpl
					14.00					

Fig. 8. Profile of research drill No. 2



Borehole	Water level depth [m p.p.t]	Stratigraphy	Scale [m]	Profile	Depth [m]	Lithological profile	Soil symbol PN -B-02480:1986	Soil symbol ISO	Moisture content	Soil condition
1	2	3	4	5	6	7	8	9	10	11
		Uncontrolled made ground				Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN	Mg	w	szg
					0.90	Uncontrolled made ground (mining waste - claystones and clayey shales, mudstones, sandstones) steel-black	nN		mw	
		Guaternary			5.30	Sandy loam	Gp	saCl	w	pl/tpl
					8.00					

Fig. 9. Profile of research drill No. 3

During the drill, resistance was used and recorded during the boring of the holes by the drilling rig.

The building design assumed the use of a direct foundation. This type of foundation would place the anthropogenic soil within the direct-activity zone, where constant and variable loads are transferred from the entire structure. For this reason, it became necessary to perform a more accurate in-situ evaluation of the anthropogenic soils with the use of the DPSH probe, which was used to make three measurements at points 1, 2, and 3 (that is, at the research points where the greatest thickness of uncontrolled ground), shown in Fig. 6.

6. Interpretation of test results obtained using the DPSH probe

The results of the measurements obtained from the DPSH soundings have been presented on the data forms in Figs. 10, 11, and 12. Density index values were determined using the dependence (6).

The soil characteristics based on o the density index I_D according to the division of non-cohesive soils specified in the standard [56] are shown in Table 2.

For the comparative analysis of the degree of soil compaction with the use of the DPSH probe, both correlation relationships were used.

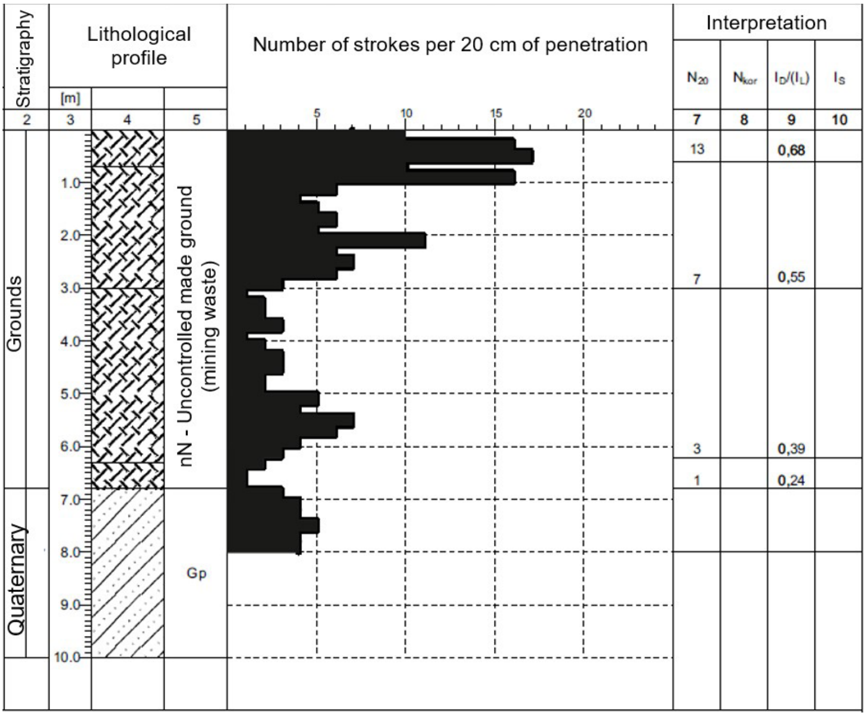


Fig. 10. Results of tests conducted using the DPSH probe in the area No. 1

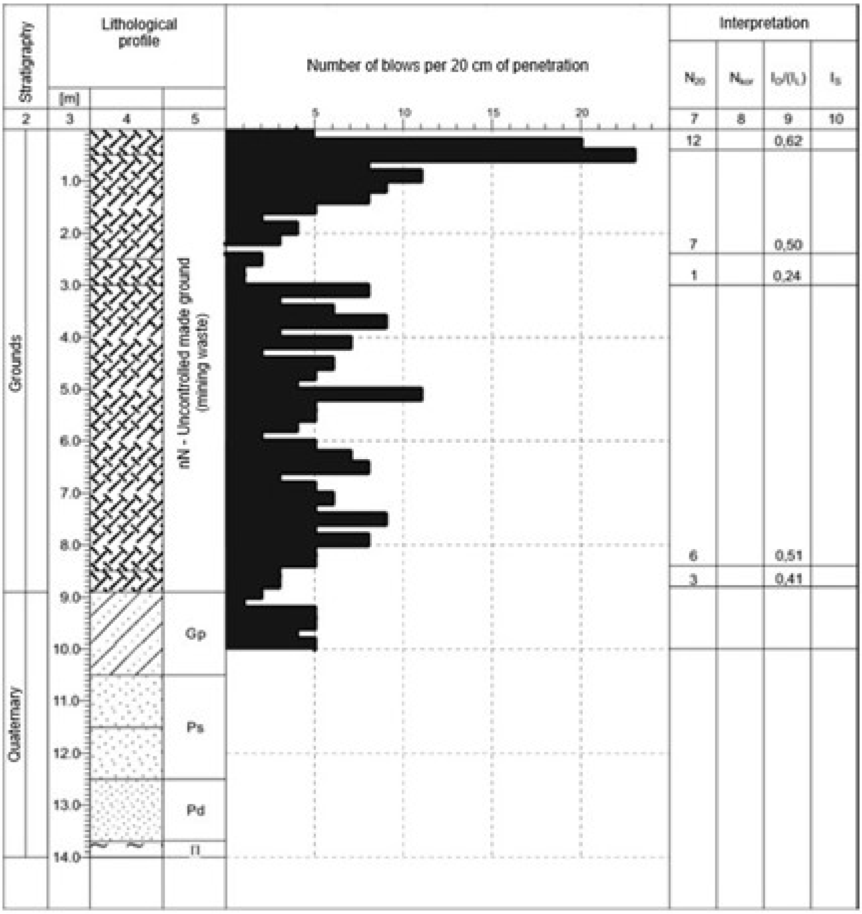


Fig. 11. Results of tests conducted using the DPSH probe in the area No. 2

Analysis of the profile DPSH 1 (boreholes No. 1)

The top layer of the uncontrolled (down to approx. 1.5 m below the surface) has been qualified as dense soil. As the depth increases from 1.5 m down to 6.0 m, the soil becomes medium-dense. Below, at the depth of the floor of the coal mining waste layer (at a depth of 6.0 to 6.8 m), the ground is loose, as shown in Fig. 10. Then, within the Quaternary sediment, the soil density increases to medium-dense. No technical irregularities were observed during the dynamic probing.

Analysis of the profile DPSH 2 (boreholes No. 2)

The made ground is classified as medium compacted in its upper part, i.e. to a depth of 2.2 m below ground level. At this depth, there is a relaxation zone (emptiness, probably resulting from the unfortunate arrangement of a layer of a large-volume embankment) within the ground. Directly below it, the made ground is classified as loose up to a depth of 3 m below ground level. Subsequent layers of the ground, i.e. from a depth of 3 m below ground level – up to 8.9 m below

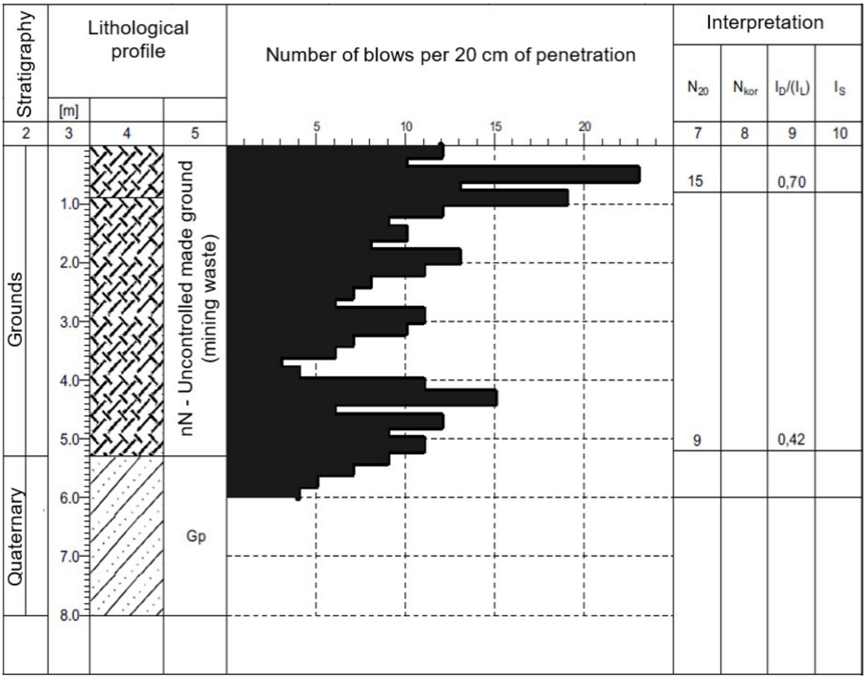


Fig. 12. Results of tests conducted using the DPSH probe in the area No. 3

ground level, are classified as medium-dense. No technical irregularities were observed during the dynamic probing.

The observed significant differences in the value of the number of probe strokes N_k, and thus the density index, may result from the accumulations of coarse-grained material with a large volume of uncompressed inter-grain voids in the measurement zone.

In borehole No. 2, the anthropogenic soil turned out to be “much more compact” than in borehole No. 1, which is indicated by the generally higher number of N20 strokes for each profile section, compared to Figs. 10 and 11. It means a significant local variation in the density and possibly also in the grain-size distribution and composition of the anthropogenic soil (mine waste).

Analysis of the profile DPSH 3 (boreholes No. 3)

The top layer of the made ground (down to approx. 0.7 m-0.9 m below the ground surface) has been classified as dense. From 0.8 m down to 5.3 metres below the ground surface, the made ground has qualified as medium-dense, except for a thin layer of loose soil, at a depth of about 4.6 m, Fig. 10. The profiles obtained in profiles DPSH 2 and DPSH 3 are similar to each other, so only in the place of DPSH 1, the conditions are slightly different than in the other locations. It should be mentioned here that during the sounding, at a depth of 0.7-0.9 metres, the number of strokes increased significantly. The above was most likely caused by the presence of larger parts of coal waste. Therefore, a greater degree of soil compaction was interpreted at the depth, in correlation with the other probes made and in correlation with the previously made test borehole (see Fig. 9).

The measurement results obtained with the DPSH probe show significant spatial differentiation of soil compaction in the studied area.

The results of the probing confirmed that the anthropogenic ground in the analysed case is characterised by an average degree of compaction in the range of I_D 0.39 ÷ 0.70, reaching even values for compacted soils, which was not found on the basis of drilling resistance during scientific work). As mentioned earlier, the analysis was based on both standards in Table 2.

TABLE 2

Division of non-cohesive soils in relation to density index according to the ISO 14688-2 and PN-86/B-02480 standards [56]

Soil compaction	Relative density [%] – ISO 14688-2	Density index PN-86/B-02480
Very lose	$I_D \leq 15\%$	
Loose	$I_D \leq 35\%$	$I_D < 33$
Medium-dense	$36\% < I_D \leq 65\%$	0,33 ÷ 0,67
Dense	$66\% < I_D \leq 85\%$	0,67 ÷ 0,80
Very dense	$I_D > 0.86$	>0,80

These issues are important factors for further design work in terms of the stability of the future building structure.

An approximate assessment of anthropogenic soil conditions obtained based on only “measurements” of drilling resistance from a drilling rig – is far from sufficient for a reliable assessment of geotechnical parameters of soils in the presence of mining waste in the excavated soils. Therefore, in such (situations described in this article and in others), the scope of geotechnical research should also be extended with known measurement techniques that will help to interpret and parameterise soils in a more detailed and precise way, in this case, on anthropogenic grounds.

It should be noted here that the use of dynamic or static soundings carried out in uncontrolled soils containing mining waste may not always be a direct basis for determining the degree of compaction of uncontrolled grounds. Anthropogenic soils, especially those with larger grain sizes, can yield a false picture of the state of this soil. When the probe tip hits larger contaminants, probe advancement is halted until the obstruction is cleared, causing the probe hit count to be greatly overestimated as 20 cm of penetration, which is the basis for interpretation. This was the case (but to a limited extent) with the probe’s impact readings, where a degree of compaction of about $I_D = 0.70$ was found. The near-surface layer of uncontrolled grounds in the area of test hole No. 3.

7. Conclusions

With the growing shortage of investment in the highly urbanised area of the USCB, it becomes necessary to use post-mining and transformed areas which have been levelled with industrial waste, especially from coal mining.

Additionally, the accumulation of large masses of waste produced by the intense 200-year mining activity in the area of USCB and the need to utilise them results in the presence of significant ground surfaces covered in managed mine waste.

The reclaimed post-mining areas are often formed by anthropogenic grounds, whose variable composition and physical conditions usually prejudge their unfitness for construction purposes.

This approach requires the use of deep soil replacement or one of the ground strengthening methods, which increases the investment costs and often turns out to be redundant if a reliable analysis of the geotechnical conditions prevailing on the construction site is performed.

The use of the super-heavy DPSH dynamic probe allows for relatively fast and effective measurements of the soil compaction of coarse-grained soils in a sufficiently large depth range.

Application of geotechnical investigations of the anthropogenic soils containing hard coal mining waste with the use of the DPSH probe influences the promotion of building construction directly on such made grounds. This is of great importance in the development of brownfields in urbanised post-mining areas.

The use of various measurement techniques determines the use of specific interpretation relationships. Several of these are rarely used to identify specific soil feature measurement techniques. This gives rise to uncritical acceptance of the interpretation result made with the use of a specific measurement technique.

Therefore, it is advisable to use different measurement techniques simultaneously to avoid interpretation errors, for example, using the CPT/CPTU static probe, i.e. the study indicated in this article. Two dynamic probings can also be used to refine the density value with different hammer weights.

Reliable measurement and interpretation results should not be interfered with by overstating or underestimating them. In this way, in accordance with the recommendation of Eurocode 7, the obtained derived geotechnical parameters can be used to obtain values as a conservative estimation of the value determining the occurrence of the limit state. When receiving geotechnical or geological documentation, the designer selects the characteristic values of geotechnical parameters himself. Sometimes these are the minimum values, and sometimes the maximum or average – from the above. When choosing the most unfavourable values, it should be guided mainly by the safety of the building under construction, making every effort to reliably assess the geotechnical situation.

In conclusion, a wide range of possible interpretations of static and dynamic probing in non-cohesive soils are currently observed. An adequate choice of one or more ways to verify the geotechnical parameters of soils, including embankment soils, will determine the correctness of further steps and design activities – for a given specific construction investment.

The article presents only one of many possible measurement and verification techniques, which in this situation, was proposed top-down. However, according to the authors of this article - the only right one at the stage of preliminary recognition of ground conditions on the analysed investment plot in terms of its suitability for future construction investments.

The article has the characteristics of a research article. It is not a new approach to such problems, but it indicates and brings the reader closer to a certain way of proceeding in such situations, where often not only the usual patterns, but intuition and practical experience determine the final effect.

Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

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