Research Article

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Assessment of surface parameters of VDW foundation piles using geodetic measurement techniques

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Abstract: This article presents *in situ* research on the side surface of Vor der Wand (VDW) foundation piles using 3D laser scanning and close-range photogrammetry to assess the morphology of pile concrete surface. Contemporary analytical methods for estimation of the bearing capacity of the foundation pile surface require determination of the parameters of the concrete roughness and the model of the surface being formed, which corresponds to the pile technology used. Acquiring these data is difficult due to the formation of piles in the ground and their subsequent work as a structure buried in the ground. The VDW pile technology is one of the widespread technologies of foundation pile used in practice. These piles exhibit a specific configuration of the lateral surface, which is related to the simultaneous use of auger drilling and casing that rotates in opposite directions. Two geodetic techniques most often used to measure the geometry of buildings are terrestrial laser scanning and close-range photogrammetry. To empirically verify the suitability of these two techniques for describing the VDW pile surface parameters, a two-stage field study was performed. In the first stage, the measurements of concrete test surfaces were conducted. This surface was formed in a smooth formwork and its roughness parameters (in accordance with ISO 25178-2: 2012) were calculated and compared with the reference surface. In the second stage, measurements of the secant VDW sheet pile wall protecting the deep excavation were carried out. The roughness parameters of the pile surface were

calculated for the selected areas in diverse geotechnical conditions. The original procedure for processing data (obtained using the above techniques) for assessment of roughness parameters of unique concrete surfaces was presented. The conducted research demonstrates that a pulse scanner has very limited usefulness for determination of roughness parameters for very smooth concrete surface; however, the photogrammetry techniques give acceptable results. In regard to the VDW pile surface, the results obtained from both measurement techniques give satisfactory consistency of the roughness parameters. The relative errors of calculated roughness parameters do not exceed 29% (average 12%). The proposed procedure may improve the accuracy of the assumed friction factor between pile surface and soil for assessment of the pile shaft bearing capacity for various pile technologies and soil conditions.

Keywords: roughness parameters, terrestrial laser scanning, close-range photogrammetry, VDW foundation piles

1 Introduction

Currently recommended and applied analytical and numerical methods for estimation of the pile shaft bearing capacity require assessment of the roughness parameters of the pile surface, which corresponds to the pile technology [1]. Acquiring these data is difficult due to the formation of piles in the ground and their subsequent work as a structure hidden in the subsoil. The standard [1] is supplemented by various European Standards dealing with more specific tasks that include the following standard: EN 1536 Execution of special geotechnical work – bored piles [2]. The need for quality management (QM) in geotechnical works including piling works is widely recognised. There are different opinions regarding a QM programme, including quality assurance (QA) and quality control (QC). QM is considered as a cooperative programme involving all parties throughout the site exploration, design, construction, testing, and acceptance process. QA is related to documented procedures

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for ensuring quality in both design and construction processes. QA is a QM tool utilised by both the design and supervision teams [3]. Design and construction processes involve tools and techniques for ensuring the quality of materials and workmanship during the construction process, thus providing QA. The techniques used in QM include visual inspection from the top of the excavation, downhole camera, shaft inspection device, and base grouting [4]. QC is defined as the verification of foundation integrity and capacity, and it utilises technologies for flaws location in material and load tests [5]. The set of QC methods used in engineering practice includes techniques of geodetic measurements. The selection of the optimal measurement technique depends on several factors, among which the most important is the availability and size of the tested building as well as the required accuracy.

The technology of Vor der Wand (VDW – original abbreviation in German or alternative name: Front of Wall – in English) pile is a measure cognate with spun concrete column. In both VDW pile technology and spun concrete technology, the concrete mixture is shaped and compacted under the action of a normal (radial) force arising during the rotational motion around the longitudinal axis of the concrete elements. Due to the fabrication process, concrete is characterised by layered structure across the wall of the annular cross-section. For assessment, the parameters describing the internal structure of concrete, for example, local strength parameters, pore space morphology, spatial distribution of aggregate and cement paste, and the methods such as micro-computed tomography (micro-CT), 2D imaging, and nano-indentation are useful [6]. The subterranean nature of pile formation makes even direct visual inspection of the final product impossible in most cases. Therefore, the presented surface investigations were carried out on the surface of the exposed wall of the excavation. Two investigative techniques were used to assess the surface roughness: photogrammetry and laser scanning. The procedures presented in the article can be included in the QC. The proposed methodology for determining the aforementioned surface roughness parameters can be a practical tool helpful, for example, in estimating pile shaft capacity in different soil types using analytical and numerical methods.

2 Geotechnical background

In this work, the surface of concrete VDW piles forming the palisade, which secures the excavation was a research

object. The set of a cased borehole with continuous flight auger drilling is called the “twin rotary head method” resulting in VDW piles. The pilling is a cast *in situ* process. By using two independent drive systems, one for casing and the other for the auger, the drive gear can be so small that the pile can be installed immediately in front of the walls of existing buildings. The upper gear propels the auger, while the lower one turns the casing in the opposite direction. The casing and auger string can be adjusted at ~300 mm to each other with a hydraulic cylinder. Optimal use of hydraulic cylinder for positioning of the auger head is possible when the lengths of the casing and the auger are matched to each other. Pile depth is controlled by the height of the drill rig. In cohesive soils or when drilling in old foundations, for primary piles and by the risk of soil collapsing, the casing is advancing the auger. In dense soil structures, drilling is advancing the casing tube. The drilling spoil is ejected to the surface by openings at the upper end of the casing. By rotating in opposite directions, the ejection of the discharge is accelerated. The borehole is filled with concrete, which is pumped by a separate concrete pump through the swivel of the auger head [7].

The unit shaft resistance $q_{s;i,k}$ between the pile and the surrounding soil is linked with soil parameters and pile surface roughness [1,8,9]. It is worth pointing out that the larger the roughness is, the higher the pile skin friction is and the higher the pile shaft capacity is [10]. The characteristic shaft resistance $R_{s,k}$ of the pile may be determined directly from the ground parameters using the following equation given in [1]:

$$R_{s,k} = \sum A_{s,i} \cdot q_{s;i,k}, \quad (1)$$

where $A_{s,i}$ is the surface area in the i th layer and $q_{s;i,k}$ is the characteristics of unit shaft resistance in the i th layer.

The standard [1] gives equation (1) for the shaft capacity; however, the problem is to determine the value q_s of unit shaft resistance. The classic formula for calculating the shaft resistance of piles q_s is given by the following equation:

$$q_s(z) = K(z) \sigma'_{v0} \tan \delta(z), \quad (2)$$

where σ'_{v0} is the effective overburden pressure at pile shaft; K is the coefficient of horizontal soil stress, which depends on the relative density and state of consolidation of the soil, the volume displacement of the pile, the material pile, and its shape; δ is the parameter contingent on soil friction angle and surface roughness.

The value K is critical to the evaluation of the shaft friction and is most difficult to determine reliably, because it is dependent on the stress history of the soil and the changes that take place during installation of the pile. The most common assumption for a cohesive and noncohesive soil is the tangent of $2/3$ or $3/4$ effective internal soil friction angle φ' as the angle δ of pile (wall) friction value for the soil–concrete interface. The shaft resistance for rough surfaces of the pile is undoubtedly greater than it is for smooth surfaces [11]. To reliably use an angle of internal friction to estimate shaft friction, a direct shear test should be carried out on the model specimen of the soil and concrete specimens with set roughness parameter. Normal stresses at the skin concrete should reflect the normal stress expected in the field [12]. As specified in ref. [13], the skin of concrete can be divided into cement skin (~ 0.1 mm thick), mortar skin (~ 5 mm skin), and concrete skin (~ 30 mm). During construction, the surface of the concrete is usually left after concreting. In some cases, it is left after contact with formwork. The latter case occurs for precast piles. In the case of piles formed in the soil, the skin of concrete is modified by soil grains. In the study by Marcon et al. [14], the potential effect of aggregate type and shape on the concrete capacity of an undercut anchor under tensile loading was investigated experimentally. A photogrammetric tool has been successfully used to gain insights in the failure mechanisms of the studied undercut anchor.

3 Methods

3.1 Principles of roughness parameters

The knowledge about areal surface texture includes diverse concepts and structures that cover specification definitions, definition categories, semantic understanding, algebraic structures, structure entities, and relationship between them. Topography of the surface is informally understood as a set of detailed three-dimensional features of a certain limited area of surface geometry. Currently, more and more academic areas and industries are beginning to apply areal surface texture measurements to investigate the quality and functional relationships of the surface. Recent technological progress in civil engineering has contributed to the development of the science surfometry concerning morphological quantitative metrology of surfaces [15,16]. Nowadays in addition to classical methods such as profilometry

and surfometry, the microstructural evaluation of the skin of concrete can be performed using X-ray micro-CT [17]. However, no applications of areal surface texture specifications exist in geotechnical design so far. It is important to provide designers with an unambiguous areal surface texture specification that is essential for safe and economical design. In the last two decades, numerous attempts have been undertaken to evaluate roughness parameters in 3D [18]. The ISO 25178 series of standards cover terms and definitions for specifications and verifications in areal surface texture. The most useful parameters for the evaluation of concrete surface morphology and their definitions are presented in Table 1. It seems that height parameters are likely to be most useful for the evaluation of concrete morphology [19].

The classification of surface roughness according to Eurocode 2 [20] distinguishes three types of surfaces: very smooth, smooth, and rough. This classification is distinctly inexact since it depends on subjective estimation of the designer. The “very smooth” surface is considered as a surface cast against steel, plastic, or specially prepared wooden moulds. The “smooth” surface is a split formed or extruded surface, or a free surface left without further treatment after vibration. The “rough” surface is a surface that has at least 3 mm roughness at about 40 mm spacing. The selection of the most relevant 3D roughness parameters is a key open problem [18]. Research is thus needed in order to develop or improve the methods of field test characterisation and assessment of concrete morphology. The next step is the necessity to develop useful algorithms for concrete morphology assessment.

Table 1: Examples of surface parameters and their definition according to [29]

Name of parameter	Definition
Height parameters	
Root-mean-square height	$Sq = \sqrt{\frac{1}{A} \iint_A (Z(x, y))^2 dx dy}$
Maximum peak height	$Sp = \sup\{Z(x_i, y_j)\}$
Maximum pit height	$Sv = \inf\{Z(x_i, y_j)\} $
Maximum height	$Sz = Sp + Sv$
Arithmetic mean height	$Sa = 1/A \iint_A Z(x, y) dx dy$
Functional volume parameters	
Peak material volume	$Vmp = Vm(p)$
Core material volume	$Vmc = Vm(q) - Vm(p)$
Core void volume	$Vvc = Vv(p) - Vv(q)$
Dale void volume	$Vvv = Vv(q)$

3.2 Terrestrial laser scanning

Terrestrial laser scanning (TLS) is now a very popular measurement technique. The principle of the scanner operation is based on reflectorless distance measurement using a laser range finder with simultaneous measurement of horizontal and vertical angles. Based on these data, the X , Y , and Z coordinates of each measured point in the local (scanner own) coordinate system are calculated and recorded. In addition, the power of laser beam reflection (so-called intensity value) from the measured object is recorded, which depends on the distance from the scanner to the measured object, angle of beam incidence, type of material, colour, and roughness of the measured surface. Moist and rusted surfaces may reduce the quality of the acquired cloud of points [21]. Shiny surfaces and elements covered with black paint sometimes prevent measurement [22,23]. Problems are also caused by atmospheric precipitation, which generates noise in the form of points reflected from raindrops or snowflakes. It sometimes limits the actual working range of the scanner and prevents the measurement of higher parts of the object (as in the case of industrial chimney described in [24]). Depending on the model, the scanners have built-in or trailed photo cameras that take a set of photos in natural colours or other spectral ranges, such as infrared [25]. It allows us to create panoramas and colouring each point in the cloud.

Laser scanners can be divided into three groups depending on how the distance is measured. The first group contains the pulse scanners that measure the time of electromagnetic wave transition between the scanner and the object being measured. The pulse scanners have a large range between 300 and 800 m and measurement speed of up to one million points per second. This type of scanners has 3D accuracy of the measured point at the level of 3 mm for distances up to 50 m. At greater distances, the accuracy of the measurement decreases. The second type is phase scanners that measure the phase changes between the sent and the returning electromagnetic wave. Phase scanners have a shorter working range of up to 350 m, but they are little faster and enable measurement with higher accuracy (position error below 1 mm for distances up to 50 m). The third type of scanners is triangulation scanners that use geometric relations in the triangle to calculate the coordinates of points representing the measured object. Triangulation scanners are built up of a beam of light projector and cameras recording the way of reflecting the light from the object being measured. They are very accurate devices with accuracy reaching hundreds or even

thousands of parts of a millimetre, but usually designed for laboratory use. The size of the object should not exceed 50 cm, and the distance to the measured object can reach up to 2 m.

When performing measurements of large buildings, it is necessary to use phase or pulse scanners and properly clean the point clouds acquired from individual scanner positions. In addition to typical filtration algorithms, a different approach can be used to estimate the 3D error of each measured point based on the position of the point and the reflectance value. Elimination of points with poor accuracy increases the quality of the acquired point cloud [26]. The next step is to combine point clouds from different scanner positions, which is called registration. This registration process involves the 3D transformation of point clouds and can be performed based on common points (signalled with special targets), by cloud-to-cloud matching or in a mixed approach. During the registration process, the location of the point cloud can also be determined in the adopted reference system (georeferencing).

3.3 Photogrammetry

Nowadays, close-range photogrammetry is very popular in many applications. The development of computational techniques has enabled the widespread use of high-resolution digital cameras with the so-called nonmetric lenses. These cheap lenses are characterised by a greater impact of distortions and aberrations on the quality of acquired images. Professional lenses are mainly used in aerial photogrammetric cameras. To increase the quality of images taken with nonmetric cameras, the calibration parameters of the lenses are calculated based on the special calibration patterns. The process of developing a 3D model of a measured object consists of several steps. Initially, the collection of photos is loaded with the initial values of lens calibration parameters. Next, the common points on images are searched and camera positions are calculated. The obtained sparse point cloud can be classified and filtered using reprojection error, reconstruction uncertainty, and projection accuracy. Based on the reference points and their coordinates or known distances between them, the camera calibration parameters can be improved (optimised) as well as the model of the measured object can be scaled. Next, the dense point cloud is built and the 3D polygonal mesh surface is generated. The last step is the texturing of geometry.

In geotechnics, the close-range photogrammetry is used among others to observe the deformation patterns due to uplift force during the investigation of the uplift resistance of short piles in loose sand [27]. Centrifuge tests performed to investigate the effects of tunnelling in sands on piled buildings are described in ref. [28]. In this case, the ground movements and displacements of model were measured using an image-based measurement technique.

3.4 Proposed procedure for determination of surface parameters

To estimate roughness parameters based on testing the concrete surfaces using two geodetic measurement techniques, the original procedure is developed and tested. In the first stage of research, the smooth concrete wall is chosen which is treated as “very smooth” surface according to ref. [20]. This surface is measured by both geodetic techniques and chosen roughness parameters are calculated according to ref. [29]. The results are compared and discussed with reference to investigation [19] and the relative error is calculated. In the second stage, the VDW pile surface is considered as a research object. These types of pile are formed *in situ* at the construction site in diverse soil conditions, so the side surface of the pile is unique and there is no reference surface defined in the literature or in the standards. The presented limitations mean that it is only possible to compare the results (roughness parameters) between two mentioned measurement techniques in the form of a relative error.

A detailed description of measurement data processing proposed by authors is presented in Figure 1. All considered samples are levelled at the first step of calculation. In comparison to the surface of wall, the samples from VDW piles had an additional step of processing (removing of the cylinder shape using the least square method). The samples obtained using laser scanning are filtered twice to minimise the measuring noise. The authors propose 3×3 median filter and 3×3 Gaussian filters. For each sample, the roughness parameters are calculated twice: before and after removing waviness (hereinafter referred to as shape removing). The waviness could be considered the specific zigzags on the VDW pile surface or unevenness of formwork in the case of a wall. The roughness parameters calculated after shape removing are indicated in the result comparison using an asterisk (*). The roughness parameters of the analysed concrete samples in accordance with ref. [29] are calculated using MountainsMap Premium v. 7.4.8803 software.

4 Description of the study sites, instrumentation, and data pre-processing

4.1 Smooth concrete surface

In the first stage of the study, a smooth vertical concrete wall was chosen and four reference points were stuck (Figure 2a). The selected fragment of the wall was 0.97 m wide and 0.76 m high (Figure 2b) and was made of concrete of class C20/25 in the formwork. It can be assumed that there is a standard “very smooth” surface made in industrial and controlled conditions. Reference points (no. 1–4) were measured using Trimble S3 total station (with an angular accuracy of 2”) in three sets, with two telescope positions (two faces) in each set (Figure 2). For all reference points, the mean error of 3D position in the local coordinate system did not exceed 1 mm. The selected fragment of the wall was measured independently using two geodetic techniques, such as close-range photogrammetry and TLS.

For photogrammetric purposes, the Nikon D800 camera with 50 mm single-focal-length lens was used. The resolution of photos was $7,360 \times 4,912$ pixels. Next, the ten photos of black-white chessboard were taken for calculation of precalibration parameters (which are juxtaposed in Table 2) in Agisoft PhotoScan Professional v. 1.2.4 software. After that, 17 photos of the concrete wall were taken and initial parameters of camera calibrations were applied. The photos were aligned with the highest accuracy (as chosen option in the software). After filtration (based on the values of reprojection error, reconstruction uncertainty, and projection accuracy), 13,342 tie points were obtained. Known coordinates of reference points were used in optimisation of camera alignment as well as to set georeferencing of the model with a total error of 0.45 mm (Table 3). The scale of the model was checked for two scale bars and the total error was 0.30 mm. Next, a dense cloud of 2,53,54,357 points was generated with ultra-high quality and aggressive depth filtering.

Laser scanning of the same smooth vertical concrete wall was performed from a single station (named SW-002) using Leica ScanStation C10 pulse scanner. According to the manufacturer specification, the accuracy of the 3D position of the single point measured using this scanner is equal to 6 mm for the distance from the scanner up to 50 m as well as the precision of the surface modelled based on the point cloud is equal to 2 mm. Field tests conducted for

Figure 1: The procedure for determining surface roughness parameters of concrete wall and concrete VDW piles based on photogrammetry and laser scanning data.

Figure 2: The concrete wall: (a) view of the research stand and (b) location of reference points.

Table 2: Precalibration parameter values calculated for Nikon D810 camera with 50 mm single-focal-length lens

Parameter	Value	Standard error
Image width	7,360	—
Image height	4,912	—
Focal length	11427.8	1.40644
Principal point (x)	28.7514	1.67598
Principal point (y)	−16.9763	1.13378
Affinity B1	0.308010	0.218018
Skew B2	−4.74729	0.215559
Radial K1	−0.138317	0.00443867
Radial K2	−0.275181	0.112754
Radial K3	3.83402	1.12883
Radial K4	−13.6624	14.9334
Tangential P1	−0.000450076	0.0000335432
Tangential P2	−0.000425979	0.0000259082

the same scanner have proved that the measurement precision at distances up to 14 m is slightly higher [5]. At the study site, the distance from the scanner to the wall was about 3.0 m and the desired resolution of point cloud was less than 1 mm in both directions (vertically and horizontally in the wall plane). The registration of cloud of 10 70 032 points in the same reference system as photogrammetry (transformation based on reference point nos 1–4) was performed in Leica Cyclone v. 9.2.1 software. The mean absolute error of registration was 0.4 mm (Table 4).

Both the point clouds (obtained from photogrammetry and laser scanning) were open in CloudCompare Stereo v.2.9.1 software and the four surface samples were selected (hereinafter referred to as samples) in the same place. The samples had the shape of squares with dimensions of 0.35 m. The samples from photogrammetry had from 30,42,240 to 31,64,412 points and were named WP1–WP4 (Figure 3a). The samples from laser scanning had 1,30,693 to 1,42,157 points and were named WS1–WS4 (Figure 3b).

4.2 Sheet pile wall

A section of VDW pile wall on the construction site was selected as a research object in the second stage of the

study. The excavation had 4.50 m depth and was located in an urbanised area (Figure 4). The piles were performed in complex geotechnical conditions. Variable colours of pile surfaces reflected layered subsoil. The subsoil was described in accordance with the standard [30]. The palisade was made of class C16/20 concrete. The length of the piles was 10.00 m and the nominal diameter was 0.52 m. Reinforcement profiles made of B500 class steel with a length of 8.0 m were installed in every other pile. The piles were constructed as secant with an overlap of about 10 cm with each other. Buildings in the vicinity of the excavation are constructed at a small depth below the ground level. Their foundations were in a poor technical condition (were generally made of solid bricks with weak lime mortar). The foundations were not resistant to horizontal displacements and unequal settlement. Therefore, execution of such construction works requires the application of appropriate technology and the protection of deep excavations, as well as the control of the excavation impact on the environment [31].

Measurement of the geometric shape of VDW piles after their excavation was performed using a TLS and close-range photogrammetry, analogous to the first stage of the study. The reference system was established using fixed wooden frame with 18 reference points (markers) forming seven scale bars. Using the same Nikon D800 camera 52 photos were taken. Initial parameters of camera calibrations were applied (Table 2) and the photos were aligned in Agisoft PhotoScan software with a chosen option: the highest accuracy. After filtration (based on the values of reprojection error, reconstruction uncertainty, and projection accuracy) and optimisation of camera alignment, the 7,740 tie points were obtained. The total error estimated from scaling the model based on 7 scale bars was equal to 0.56 mm (Table 5). Next, a dense cloud of 4,03,80,435 points for the chosen area was generated with ultra-high quality and aggressive depth filtering.

Laser scanning of the same area was performed from two stations using Leica ScanStation C10 pulse scanner. The distances to pile surfaces were about 6.4 and 7.6 m.

Table 3: Estimation of photogrammetric model accuracy for smooth concrete wall based on known coordinates of reference points

Label	X (m)	Y (m)	Z (m)	Accuracy (m)	Error (m)	X error (m)	Y error (m)	Z error (m)
1	−0.47304	0.36139	0.00029	0.00090	0.00044	−0.00031	−0.00027	0.00016
2	0.49235	0.39053	−0.00019	0.00040	0.00023	0.00022	0.00005	−0.00003
3	−0.50206	−0.38094	−0.00011	0.00090	0.00051	0.00031	−0.00037	−0.00015
4	0.48329	−0.37081	0.00004	0.00060	0.00054	−0.00050	0.00017	0.00007
Total error					0.00045	0.00035	0.00025	0.00011

Table 4: Report of point cloud registration in Cyclone software for smooth concrete wall

Constraint ID	Scan-world	Scan-world	Type	Status	Weight	Error (mm)	Error vector (mm)	Horizontal error (mm)	Vertical error (mm)
1	Reference points (levelled)	SW-002	Coincident: vertex-vertex	On	1.0	0.4	(-0.2, 0.3, 0.1)	0.4	0.1
2	Reference points (levelled)	SW-002	Coincident: vertex-vertex	On	1.0	0.3	(0.2, -0.1, -0.1)	0.3	-0.1
3	Reference points (levelled)	SW-002	Coincident: vertex-vertex	On	1.0	0.6	(0.5, -0.3, -0.1)	0.6	-0.1
4	Reference points (levelled)	SW-002	Coincident: vertex-vertex	On	1.0	0.5	(-0.5, 0.1, 0.1)	0.5	0.1
Mean absolute error						0.4	—	—	—

The desired resolution of point cloud was 1 mm in both directions (vertically and horizontally). The registration was performed in Leica Cyclone software based on three reference targets mounting on tripods and located around the construction site (Figure 4). The mean absolute error of registration was 0.2 mm (Table 6). The obtained point cloud had 2,47,85,940 points.

Both the point clouds (obtained from photogrammetry and laser scanning) were open in CloudCompare software and the two surface samples were selected (hereinafter referred to as samples) in the same place. The samples had the shape of a square with dimensions of 0.35 m. The samples from photogrammetry had 5,83,275 points for the PP1 sample and 5,65,367 points for the PP2 sample (Figure 5a). The samples from laser scanning had 3,61,669 points for the PS1 sample and 2,61,615 for the PS2 sample (Figure 5b). The samples with suffix “1” (PP1 and PS1) represented pile surface moulded in the native soil (silty/medium sand) and samples with suffix “2” (PP2 and PS2) represent the earthwork (fill ground).

5 Test results

This section presents the results of tests and their statistical characteristics for the roughness parameters obtained on the smooth concrete wall surface by photogrammetry (Figure 6) and laser scanning (Figure 7). The results presented in Figure 8 suggest that the estimated roughness parameters vary significantly among both techniques.

This section presents the results of tests of the roughness parameters obtained on VDW pile surfaces. The 3D view of samples obtained from both measurement techniques for native soil is presented in Figure 9 and for earthwork is presented in Figure 10. The selected roughness parameters of VDW piles calculated based on photogrammetry and laser scanning for samples from native soil are juxtaposed in Figure 11 and for samples from earthwork in Figure 12.

In Figures 8, 11 and 12, the results of the roughness parameters for two different areas, smooth concrete surface and VDW pile surface, are shown. For samples representing the surface of smooth concrete, the values S_a and S_q are similar to each other and they are less than 1 mm. The surface of smooth concrete is characterised by high smoothness uniformity. Therefore, the measurement noise resulting from the limited accuracy of the scanner and applied filtering does not significantly affect

Figure 3: Numbering of surface samples on the concrete wall from (a) photogrammetry and (b) laser scanning.

the values of these parameters. Individual local cavities (craters and crampons, honeycombing in concrete), irregularly distributed on the sample surface, cause disturbance and dispersion of skewness and kurtosis. The measuring noise of the scanner causes the value of parameters Sp , Sv , and Sz to be overestimated twice with the results obtained from photogrammetry. A similar tendency can be observed for the parameters Sk , Spk , and Svk and for volumetric parameters V , where the overvaluation is approximately three times. The removal

of the residual effect of unevenness in the form of formwork (shape removing using the fifth-degree polynomial) reduces the scatter of results for samples measured with the photogrammetric technique, but no such effect has been obtained for the data from scanning. Using the pulse scanner to assess the surface roughness of concrete, the authors were aware of the limited accuracy of this instrument. This was confirmed by differences in the value of calculated roughness parameters based on point clouds obtained from both measurement techniques. For precast

Figure 4: View of the excavation with sheet VDW pile wall, research stand, and reference points on tripods for laser scanner.

Table 5: Estimation of photogrammetric model accuracy for VDW piles based on known distances between reference points

Scale bar label	Distance (m)	Accuracy (m)	Error (m)	Estimated distance (m)
2–3	0.4766	0.0005	0.00088	0.47748
4–5	0.3436	0.0005	0.00042	0.34402
5–6	0.3666	0.0005	0.00003	0.36663
7–8	0.4107	0.0005	–0.00036	0.41034
8–9	0.3710	0.0005	–0.00051	0.37049
H1–H2	0.4462	0.0005	0.00052	0.44672
H5–H6	0.4349	0.0005	–0.00076	0.43414
Total error			0.00056	

piles, which are produced in accordance with the technological requirements, in closed industrial hall conditions, a better measuring tool will be a triangulation scanner with higher accuracy of the measurement. In the photogrammetric technique, the accuracy of the reconstruction of the 3D geometry of an object based on photographs depends on many factors. The most important of them is the location of the projection centres of each photo, lighting, and the surface colour of the measured object. In the analysed case, the geometry of the wall and the relatively homogeneous surface colour make it difficult. Nevertheless, the photogrammetric technique gives satisfactory results, also in construction site conditions.

On the surface of the VDW pile, two research areas have been separated, such as sample with suffix “1” made in the native soil (silty sand/medium sand) and sample with suffix “2” made in earthwork (fill ground). Both measuring techniques provided similar roughness parameters. The obtained consistency of results is much higher than for the surface of the concrete wall. On sample with suffix “1”, there were visible characteristic regular zigzags. Height parameters calculated based on data from laser scanning are slightly higher (about 10%) in relation to data from photogrammetry. The use of shape removing (zigzags) with the seventh-degree polynomial lowered the values of height parameters for both measuring techniques in a similar range. Similar observations can be seen by analysing surface and volume parameters.

Sample with suffix “2” was characterised by a greater irregularity because the pile was made in heterogeneous soil in terms of lithology and physical properties of soil. Concrete applied under pressure during the formation of the pile randomly displaces soil particles of different densities and weights in this layer. The calculated roughness parameters (for both measurement techniques) have slightly higher values in comparison to the results for the

Table 6: Report of point cloud registration in Cyclone software for VDW pile wall

Constraint ID	Scan-world	Scan-world	Type	Status	Weight	Error (mm)	Error vector (mm)	Horizontal error (mm)	Vertical error (mm)
A	SW-001 (levelled)	SW-002 (levelled)	Coincident: vertex–vertex	On	1.0	0.2	(0.0, –0.2, 0.0)	0.2	0.0
B	SW-001 (levelled)	SW-002 (levelled)	Coincident: vertex–vertex	On	1.0	0.3	(0.1, 0.2, –0.2)	0.2	–0.2
C	SW-001 (levelled)	SW-002 (levelled)	Coincident: vertex–vertex	On	1.0	0.2	(–0.1, 0.0, 0.2)	0.1	0.2
Mean absolute error						0.2	–	–	–

Figure 5: Location and numbering of surface samples on the sheet VDW pile wall from (a) photogrammetry and (b) laser scanning.

sample with suffix “1”. Obtained satisfactory agreement of the results describing the VDW pile surface roughness parameters from both measurement techniques confirms the usefulness of a pulse scanner for measuring concrete surfaces formed in the subsoil.

6 Discussion

Comparison of roughness parameter values from various studies previously described in the literature is difficult to carry out due to the following factors:

- concrete surface tests described in the literature are usually carried out in laboratory conditions, where the environmental conditions are stable and there are no disturbances, for example, in the form of vibrations caused by machines at the construction site;
- the dimensions of samples tested in the laboratory and the distance to the measuring instrument are small, which allows the use of measuring techniques with high accuracy of surface mapping, for example, triangulation scanners;
- the class of concrete and the grain-size curve of the tested samples described in the literature are varied, which affects roughness parameters;
- tests of concrete surfaces prepared by industrial methods (e.g., shot blasting, grinding) are used to assess the shear strength between concrete layers [32] and in pull-off adhesion tests [19];

- VDW pile side surfaces are unique and depend on pile forming technology and the type of soil surrounding the pile.

Laser scanning and close-range photogrammetry are typical measuring techniques available on construction sites. To verify the usefulness of these methods for determining roughness parameters, reference measurements of the smooth concrete wall were carried out. In civil engineering standards, there are no concrete reference surfaces for roughness testing, and there are only qualitative descriptions. The samples considered in this article (representing the surface of smooth concrete) can be compared with the tests carried out in ref. [19] and [32]. Parameters specified in ref. [32] were obtained using a profilometer for surface testing and cannot be directly compared with areal surface parameters. According to ref. [32], the volumetric parameters have a significant impact on the shear strength between concrete and other materials. Results of roughness parameters for smooth concrete surface presented in ref. [19] were adopted as reference values. A list of reference roughness parameters and the values of parameters obtained by the authors using photogrammetry and laser scanning are presented in Table 7. Reference tests described in ref. [19] were carried out for two types of concrete surfaces, such as surface left after concreting and concrete subjected to mechanical grinding with dust removal. The first one can be

Figure 6: Results of surface processing for samples: WP2 (a–c) and WP4 (d–f) obtained from photogrammetry, according to the procedure presented in Figure 1. (a) Extracted point cloud, (b) after levelling, (c) after shape removing, (d) extracted point cloud, (e) after levelling, (f) after shape removing.

described as “rough” and the second one as “very smooth” surface according to ref. [20]. The values of roughness parameters obtained by the photogrammetry technique are roughly similar to the reference results for “very smooth” surface, which allows us to recommend this technique for *in situ* testing of surface morphology. Compliance of volumetric parameters is important because these parameters were identified as surface parameters that best correlate with bond strength of concrete-to-concrete and concrete-to-soil interfaces. Primary parameters, in particular, based on extreme values (maximum peak height S_p , maximum pit height S_v), are usually influenced by the existence of deep air holes in

the measuring sample. For flat surfaces, removing the shape has no significant justification and does not significantly change the results.

Due to the lack of reference tests for VDW piles, it is only possible to compare the compatibility of surface parameters obtained from both measurement techniques (Table 8). For sample moulded in the native soil (sample name with suffix “1”), the relative error of surface parameters determination does not exceed 23% (for samples before shape removing) and 29% (for samples after shape removing). The average values of these relative errors are 12% and 17%, respectively. For sample formed in earthwork (sample name with suffix “2”), the

Figure 7: Results of surface processing for samples: WS2 (a–d) and WS4 (e–h) obtained from laser scanning, according to the procedure presented in Figure 1. (a) Extracted point cloud, (b) after levelling, (c) after filtering, (d) after shape removing, (e) extracted point cloud, (f) after levelling, (g) after filtering, (h) after shape removing.

relative errors of surface parameter determination do not exceed 19% (for samples before shape removing) and 22% (for samples after shape removing). The average values of these relative errors are 6% and 12%,

Figure 8: Box plot comparison of roughness parameters of the precast concrete surface obtained using photogrammetry: WP, WP* (after shape removing) and from laser scanning: WS, WS* (after shape removing).

respectively. The differences in roughness parameters determined from both measuring techniques are lower for the rough VDW pile surface than for the smooth

concrete wall. According to the authors, it is caused by the smaller impact of the scanner measuring noise during scanning the samples with high surface variation

Figure 9: Results of surface processing for samples: PP1 (a–d) and PS1 (e–h), according to the procedure presented in Figure 1. (a) Extracted point cloud, (b) after levelling, (c) after removing of cylinder shape, (d) after shape removing, (e) extracted point cloud, (f) after levelling, (g) after removing of cylinder shape and filtering, (h) after shape removing.

than scanning flat samples. The practical application of the presented methods consists in estimation of the values of roughness parameters in different layers and, consequently, a more accurate pile shaft capacity

Figure 10: Results of surface processing for samples: PP2 (a–d) and PS2 (e–h), according to the procedure presented in Figure 1. (a) Extracted point cloud, (b) after levelling, (c) after removing of cylinder shape, (d) after shape removing, (e) extracted point cloud, (f) after levelling, (g) after removing of cylinder shape and filtering, (h) after shape removing.

assessment for various technologies. In the considered case, the determination of the shaft capacity based on data from laser scanning will give higher (probably overestimated) values of capacity.

Figure 11: Selected roughness parameters of VDW piles obtained using photogrammetry: PP1, PP1* (after shape removing) and using laser scanning: PS1, PS1* (after shape removing).

Figure 12: Selected roughness parameters of VDW piles obtained using photogrammetry: PP2, PP2* (after shape removing) and using laser scanning: PS2, PS2* (after shape removing).

Table 7: List of parameters from the laboratory reference test (mechanical grinding with dust removal described in [19]) and from the field test

Parameter symbol (unit)	Reference test value	Techniques, parameter values, and relative error			
		Photogrammetry	Relative error (%)	Laser scanning	Relative error (%)
Sq (mm)	0.253	0.173	46	0.641	153
Sp (mm)	0.665	0.486	37	2.660	300
Sv (mm)	1.269	2.539	50	4.442	250
Sz (mm)	-0.604	3.025	120	7.102	1276
Sa (mm)	0.198	0.142	39	0.510	158
Vmp (mm ³ /mm ²)	0.008	0.005	60	0.028	250
Vmc (mm ³ /mm ²)	0.225	0.164	37	0.576	156
Vvc (mm ³ /mm ²)	0.256	0.193	33	0.770	201
Vvv (mm ³ /mm ²)	0.037	0.021	76	0.075	103

Table 8: Comparison of calculated surface parameters for both measuring techniques (before and after shape removing) for VDW piles

Parameter symbol	Unit	PP1 sample	PS1 sample	Relative error (%)	PP2 sample	PS2 sample	Relative error (%)
Before shape removing							
Sq	mm	2.115	2.265	7	3.115	3.220	3
Sp	mm	7.803	9.228	18	13.739	13.943	1
Sv	mm	6.405	7.860	23	13.531	11.600	14
Sz	mm	14.208	17.088	20	27.271	25.544	6
Sa	mm	1.708	1.834	7	2.477	2.559	3
Vmp	mm ³ /mm ²	0.116	0.120	3	0.138	0.164	19
Vmc	mm ³ /mm ²	2.001	2.095	5	2.883	2.976	3
Vvc	mm ³ /mm ²	2.572	2.875	12	3.686	3.767	2
Vvv	mm ³ /mm ²	0.183	0.201	9	0.371	0.361	3
After shape removing							
Sq	mm	1.662	1.826	10	1.611	1.849	15
Sp	mm	5.832	7.539	29	6.001	6.177	3
Sv	mm	5.534	6.750	22	7.212	7.746	7
Sz	mm	11.366	14.289	26	13.213	13.923	5
Sa	mm	1.379	1.494	8	1.268	1.471	16
Vmp	mm ³ /mm ²	0.061	0.073	21	0.063	0.077	22
Vmc	mm ³ /mm ²	1.622	1.703	5	1.414	1.675	18
Vvc	mm ³ /mm ²	2.226	2.485	12	1.871	2.141	14
Vvv	mm ³ /mm ²	0.136	0.162	19	0.221	0.236	7

7 Conclusions

This article presents the application of laser scanning and photogrammetry for concrete surface morphology assessment. Two types of concrete surfaces differing in the formation method were examined. For “very smooth” concrete wall, the measuring noise of the pulse scanner has a significant influence on the value of the estimated surface roughness parameters and limits the practical application of this type of scanner. However, the results obtained from both measurement techniques give satisfactory consistency for describing

the VDW pile surface roughness parameters (relative error does not exceed 29%; on average 12%). It confirms the usefulness of a pulse scanner for measuring concrete surfaces formed in the subsoil. For heterogeneous surfaces, the scanner noise (using the proposed spatial filters) has an unimportant influence on the estimated roughness parameters in comparison to results obtained from photogrammetry, which can be treated as a more accurate technique. The experiments have demonstrated that selection of the optimal measurement technique depends on several factors, the most important of which is the availability,

size, and nature of the tested surface. The photogrammetry technique could be used for surface investigation in the laboratory as well as in the construction site. The accuracy of the pulse scanner is accepted for field investigation of geotechnical construction; however, for laboratory tests, the accuracy of this type of instrument should be improved by using the phase scanner or triangulation scanner.

It is worth noting that further investigations are required to terminate limitations and particularly to compare results with different instruments with higher accuracy. It also seems that examined 3D roughness parameters will be useful for the analysis of concrete surface morphology for identification of the pile shaft bearing capacity.

Considering the geotechnical applications of the results, the questionable issue mentioned by authors is performing of shape removing, recommended by the ISO 25178-2: 2012 standard. In the case of VDW piles, whose lateral surface is complicated (e.g., zigzags), the shape removing results in a decrease in the volume parameter values, which reduces the assessment of VDW pile shaft capacity.

The obtained values of roughness parameters have a potential practical significance and can be enhanced in further research by increasing the number of surface samples and including another pile technology to predict pile bearing capacity more reliable based on the geodetic measurement techniques.

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References

- [1] EN 1997-1 Eurocode 7: Geotechnical design – Part 1: General rules, 2009.
- [2] European Committee for Standardization, PN-EN 1536:2015, Execution of special geotechnical work – Bored piles, 2015.
- [3] Sobala D, Rybak J. Role to be played by independent geotechnical supervision in the foundation for bridge construction. *IOP Conf Ser Mater Sci Eng.* 2017;245:1–8.
- [4] Hertlein B, Verbeek G, Fassett R, Arnold M. A comparison of quality management for bored pile/drilled shaft (BP/DS) foundation construction and the implementation of recent technologies. *DFI J – J Deep Found Inst.* 2016;10:87–94.
- [5] Muszyński Z, Rybak J, Kaczor P. Accuracy assessment of semi-automatic measuring techniques applied to displacement control in self-balanced pile capacity testing appliance. *Sensors.* 2018;18:4067.
- [6] Michalek J, Pachnicz M, Sobótka M. Application of nano-indentation and 2D and 3D imaging to characterise selected features of the internal microstructure of spun concrete. *Materials.* 2019;12:1016.
- [7] Woodward J, Tomlinson M. Pile design and construction practice. 6th ed. Baton Rouge: CRC Press; 2014.
- [8] Canakci H. Pile foundation design using Microsoft Excel. *Comput Appl Eng Educ.* 2007;15:355–366.
- [9] Coduto DP, Kitch WA, Yeung MR. Foundation design: principles and practices. 3rd ed. Harlow, UK: Pearson; 2015.
- [10] Wrana B. Pile load capacity – calculation methods. *Stud Geotech Mech.* 2015;37:83–93.
- [11] Zhu J-G, Shakir RR, Yang Y-L, Peng K. Comparison of behaviors of soil-concrete interface from ring-shear and simple shear tests. *Yantu Lixue/Rock Soil Mech.* 2011;32:692–696.
- [12] Ilori AO, Udoh NE, Umengue JI. Determination of soil shear properties on a soil to concrete interface using a direct shear box apparatus. *Int J Geo-Eng.* 2017;8:17.
- [13] Kreijger PC. The skin of concrete composition and properties. *Matériaux Constr.* 1984;17:275–283.
- [14] Marcon M, Ninčević K, Boumakis I, Czernuschka L-M, Wan-Wendner R, Marcon M, et al. Aggregate effect on the concrete cone capacity of an undercut anchor under quasi-static tensile load. *Materials.* 2018;11:711.
- [15] Leach R. Optical measurement of surface topography. Berlin Heidelberg, Germany: Springer Berlin Heidelberg; 2011.
- [16] Leach RK. Characterisation of areal surface texture. Berlin Heidelberg, Germany: Springer; 2013.
- [17] Sadowski Ł, Stefaniuk D. The effect of surface treatment on the microstructure of the skin of concrete. *Appl Surf Sci.* 2018;427:934–41.
- [18] Pagani L, Qi Q, Jiang X, Scott PJ. Towards a new definition of areal surface texture parameters on freeform surface. *Measurement.* 2017;109:281–291.
- [19] Hola J, Sadowski L, Reiner J, Stach S. Usefulness of 3D surface roughness parameters for nondestructive evaluation of pull-off adhesion of concrete layers. *Constr Build Mater.* 2015;84:111–120.
- [20] EN 1992-1-1:2004 Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings, 2004.
- [21] Muszyński Z, Rybak J. Evaluation of terrestrial laser scanner accuracy in the control of hydrotechnical structures. *Stud Geotech Mech.* 2017;39:45–57.
- [22] Muszyński Z. Displacement measurements of the statue of Christ the King in Świebodzin – first results. In: International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM. Albena, Bulgaria: International Multidisciplinary Scientific GeoConference; 2015.

- [23] Muszyński Z. Assessment of suitability of terrestrial laser scanning for determining displacements of cofferdam during modernization works on the Rędzin sluice. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*; 14th International Multidisciplinary Scientific Geoconference and EXPO, SGEM 2014, International Multidisciplinary Scientific GeoConference SGEM. Albena, Bulgaria: International Multidisciplinary Scientific Geoconference; 2014. p. 81–88.
- [24] Muszyński Z, Milczarek W. Application of terrestrial laser scanning to study the geometry of slender objects. In: Drusa M, Torok I, Ferrero AM, Yilmaz I, Marschalko M, Karaca O, editors. *IOP Conference Series: Earth and Environmental Science*. Wroclaw, Poland: Institute of Physics Publishing; 2017. p. 1–7.
- [25] Głowacki T, Muszyński Z. Analysis of cooling tower's geometry by means of geodetic and thermovision method. *IOP Conference Series: Materials Science and Engineering*. Moscow, Russia: Institute of Physics Publishing; 2018.
- [26] Ozendi M, Akca D, Topan H. An empirical point error model for TLS derived point clouds. *Int Arch Photogramm Remote Sens Spat Inf Sci – ISPRS Arch*. 2016;41:557–63.
- [27] Faizi K, Jahed Armaghani D, Sohaei H, Rashid ASA, Nazir R. Deformation model of sand around short piles under pullout test. *Meas J Int Meas Confed*. 2015;63:110–9.
- [28] Franza A, Marshall AM. Centrifuge modelling of piled structure response to tunnelling. In: *Proceedings of the 3rd European Conference on Physical Modelling in Geotechnics (Eurofuge 2016)*. Nantes, France: IFSTTAR The French Institute of Science and Technology for Transport, Development and Networks; 2016.
- [29] PN-EN ISO 25178-2:2012. Geometrical product specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters (ISO 25178-2:2012); 2012.
- [30] EN ISO 14688-1:2018-05 Geotechnical investigation and testing – identification and classification of soil. – Part 1 Identification and description; 2018.
- [31] Berkowski P, Dmochowski G, Minch M, Szolomicki J. Structural and geotechnical diagnostic procedure for historical buildings exposed to the influence of deep excavations – a case study. In: Van Balen K, Verstrynghe E, editors. *Structural Analysis of Historical Constructions: Anamnesis, Diagnosis, Therapy, Controls: Proceedings of the 10th International Conference on Structural Analysis of Historical Constructions (SAHC 2016)*. Leuven, Belgium: CRC Press/Balkema; 2016. p. 473–80.
- [32] Santos PMD. Assessment of the shear strength between concrete layers. Coimbra, Portugal: University of Coimbra; 2009.