Quality of surface geostatistical parameter reproduction for laser profilometers

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Abstract. The description of the surface topography of building structures is important for contact tasks, bond strength and rheological processes monitoring. The determination of surface parameters is carried out using increasingly sophisticated methods and techniques, such as laser profilometer, laser scanner, confocal microscope or short range photogrammetry. The research is aimed at evaluating the mobile surface test device for quality control and failure prevention, also the authors have addressed the possibility of using inexpensive profile measuring laser equipment to obtain a geostatistical description of the surface parametrics. It is the support of creation of new measurement apparatus that is the impetus for this work for the selection of optimal laser device. It is possible to deduce from the paper how the density of measurements taken and the accuracy of height estimation in the profile affect the parameters of the semivariogram model. With the proper choice of device it is easier correctly estimate the strength parameters of the joint of concrete or soil-concrete structures. The relevance of the correctly performed measurement is proved by the link between the strength parameters of the contact surfaces and its geostatistical description. In order to assess the quality of the mapping, a spherical theoretical model with a corresponding generated surface was used as a reference. The measuring laser devices with various mapping accuracy and depth measurement precision were tested, also for description fractal dimension of results. The measurement accuracy of the depth parameter has the greatest influence for determination of the remaining parameters of the surface roughness.

1. Introduction
The monitoring of building structures is an important element in disaster risk management. Both deformations of entire structures and their elements are monitored. The presented concept allows to identify irregularities even at the stage of qualification of surfaces for building. In the phase of erection of the objects the estimation of the contact roughness is very important e.g. monolithic constructions consisting of successively performed layers, combination of geotechnical and concrete constructions. The knowledge about the contact features will to a large extent allow to prevent damages of the structures increasing their durability and safety.
Topography descriptions of a concrete surface are usually aimed at improving the quality of joints between concrete elements. Appropriate preparation of concrete surfaces is also important for the achieved adhesion of structural layers connected with concrete. Various surface treatment technologies and modification of surface parameters [1, 2] are used. Studies of impact of the concrete surface treatment on its roughness and results of the pull out tests are presented in the works of [3, 4].

The need for universal methods to describe the surface led to the dynamic development of methods and parameters used for quantitative description of the surface irregularities, mostly in deterministic form. Currently, the principles of measurements and definitions of parameters that numerically describe the surface irregularities are normalized [5]. The profilometers may determine reliable values for deterministic surface roughness parameters. A limited summary from wide spectrum measurement methods is shown in table 1 [2].

| Name                      | Non destructive | Associated costs | Contact with surface |
|---------------------------|-----------------|------------------|----------------------|
| Sand patch test           | yes             | low              | yes                  |
| Mechanical stylus         | yes             | medium           | yes                  |
| Confocal microscopy       | no              | high             | no                   |
| Ultrasounds               | yes             | medium           | yes                  |
| Laser profilometer        | yes             | medium           | no                   |
| Close range photogrammetry| yes             | high             | no                   |

Topography of the surface is informally understood as a set of detailed three-dimensional features of a certain limited area of surface. Part of the terminology associated with surface topography was taken from a two-dimensional description of the roughness prepared for profiles. 2D measurements refer to the profile and they are determined by measurements of profile irregularities, whereas 3D measurements refer directly to the surface and they are described as measurements of topography, measurements of stereometry or stereometric measurements. In order to conduct a comprehensive roughness analysis, around sixty 3D roughness parameters were created to describe most of the surface morphology with regard to specific functions, properties or applications. In the last two decades, numerous attempts have been undertaken to evaluate roughness parameters in 3D. In order to limit the increasing number of such parameters and to standardize their use standard [5] was developed. In many fields of mechanics and construction, stochastic description of material properties displaces deterministic approaches (an example is a set of EuroCod standards), models have already been developed introducing geostatistical description to surfaces [6] and indicating its relation with contact strength properties.

Concrete, rock, and core samples all have an important characteristic in common - their surface roughness and topography can play a vital role in applied use and an explanation to fracture and interaction. For example, concrete surface roughness can play a crucial role in the bonding to applied substrates. This measurement requires a portable, reliable and common instrument. The effect of concrete surface on adhesion is not quite clear [3]. It is generally assumed that an increase in roughness of the concrete substrate would enhance the adhesion with material and concrete substrate. However, some authors [4, 7] state that surface roughness itself does not have a crucial influence.
on the adhesion especially in the case of fissured material. It should be noted that the proper preparation of the connection layer, describable by surface roughness parameters, has a significant influence on the mutual adhesion [8].

Construction joints are well known and can be of basically two types. Type 1 is when the construction joint is designed, therefore the engineer is able to take into consideration the circumstances of casting, to prescribe how to prepare the old concrete surface, even to prepare load transferring teeth and the time elapsing between the casting of the two interlocking layers is less than one year. Type 2 is when the construction joint is formed accidentally, or due to a much later (may be counted even in years) decision then the old concrete was cast [1, 9, 10].

In case of both concrete contact categories, standards defined only two domains of parameters: smooth or rough, but without correlated numerical values [11].

2. Method of measurements

Laser profilometers (figure 1) based on a CMOS detection line method are evaluated from optical profilometers which were a widespread technique [12, 13].

![Figure 1. Functional diagram of laser profilometers a) 1D, b) 2D,](image)

\( V_{in} \) - power supply, \( I^2C \) data exchange protocol Inter-integrated circuit (serial bus), CMOS complementary-symmetry metal–oxide–semiconductor has got the precise laser beam position indicator, controller manages device and communications

The sample surface is scanned with a controlled laser beam. The objective position is a measure of the local surface topography. A similar principle of operation is used in compact disc CDs, in binary logic. For this reason, CD pickups are widely used for optical profilometry [14]. The use of CD pickups in optical profilometry was a common practice. The typical instruments parameters presented in table 2.

| Table 2. Micro laser distance sensor HG-C series of CMOS type |
1) Popular class type device for detection purposes based on Time-of-Flight ToF laser-ranging module. The VL53L0X integrates a leading-edge array Single Photon Avalanche Diodes SPAD and embeds ST’s second generation FlightSense™ patented technology.

2.1. Geostatistic

To analyze the roughness geostatistical methods were used. The formalization of these methods began in the 1960s with the French mathematician and engineer Professor Georges Matheron [15]. Initially, geostatistics was used in the mining industry. Currently, geostatistics methods are used in many other areas such as geology, hydrology, and structural engineering [16]. In the analyzed case, geostatistical methods were used to fit the theoretical semivariograms to the empirical data of the model surfaces. Semivariograms are one of the most widely used geostatistical tools. They are used to measure the spatial autocorrelation of regionalized variables. They provide information about the spatial continuity and variability of the random function.

To build the empirical semivariogram were used the "z" values, i.e. the measured heights. To best fit the semivariogram to the empirical data, the LSM and the Gauss-Newton algorithm was used. The major formula of the semivariogram used is described by the equation (1), where for each \( h \), half of the mean value of the squared difference \( z(d) - z(d + h) \) is defined as semivariance with a squared length unit.

\[
\gamma(h) = \frac{1}{2N} \sum_{i=1}^{N} (z(d) - z(d + h))^2 \quad \{d, d + h\} \in P
\]  

(1)

Where \( z(d) \) are normalized “z” coordinates at location \( d \), \( h \) is the lag distance, i.e., the distance that separates the two analyzed locations, and \( N \) is a number of all tested pairs \( \{d, d + h\} \) from space \( P \). In the literature [17, 15], apart from semivariograms, variograms are quite often used, which are referred to as 2\( \gamma(h) \), i.e. twice the semivariogram.

If any two points are at a small distance from each other, we expect a small value of the measure \( (z(d) - z(d + h))^2 \). Whereas, when the lag distance between two points increases, the differences of measured values expand. This phenomenon can be represented by many theoretical relationships, the most popular of which are: nugget, linear, spherical, exponential and gaussian. Each of them is described by two parameters \( r \) (range) - the distance at which the obtained values are flattened and \( s \) (sill) - the maximum variance.
(sill) - the value of the semivariogram in the range. The most important factor in the selection of the theoretical model of the semivariogram should be the convergence of the empirical semivariogram, which can be checked using the likelihood function or the method of minimizing the sum of the square of the LSM deviations. In some cases, other factors such as the flexibility of the model or the simplicity of calculations may be taken into account.

In theory, if the separation distance is zero, the value of the semivariogram should be zero. However, many of the observed semivariograms do not approach zero with decreasing separation distance. This observation is called the nugget effect, due to the characteristic semivariogram appearance for gold deposits [17]. The nugget effect implies sudden changes in the semivariogram value at small lag distances. Whether this phenomenon will occur depends on attributed measurement error or spatial sources of variation at distances smaller than the sampling interval, or both.

2.2 Fractal task dimension

A unique property of rough surfaces is that if a surface is repeatedly magnified, increasing details of roughness are observed right down to nanoscale. In addition, the roughnesses at all magnifications appear quite similar in structure. The statistical self-affinity is due to similarity in appearance of a profile under different magnifications. Such a behavior can be characterized by fractal geometry [18-20]. The fractal approach has the ability to characterize surface roughness by scale-independent parameters and provides information on the roughness structure at all length scales that exhibit the fractal behavior.

Fractal analysis was used to characterize the self-similarity of the subgrade stiffness profile. The fractal dimension [21] was estimated using the Box-count method. The idea of the method is determining the smallest number of necessary rectangles needed to cover the area under a set of measured modules depending on their position. Using the box counting method, the fractal dimension is against the slope of the line when we plot the value of \( \log N \), where \( N \) is a number of boxes that cover surface under points, on the E axis against distance axis:

\[
\tilde{D} = \frac{\log N}{\log r}
\] (2)

The value of \( \log r \) is connected with magnification or inverse of box size. For an ideal fractal surface, equation (2) relays the tilting angle of a doubly logarithmic graph of relative area since all scales are covered, including \( r = 1 \) (at this point, \( N \) is also 1).

3. Results and discuss

We considered the surface defined by the spherical model with the parameters: no nugget effect, variation (sill) 1.0 mm², threshold (range) 10.0 mm. A sample with a constant mean height of \( z = 0 \) mm, and isotropic surface was assumed. A random field corresponding to the model of figure 2 was generated, where the heights (\( z \)) were mapped using colors.
Fig. 2. Artificial generated model (254 dpi resolution) intense of gray is proportional to depth above average level, ce roughness

The square surface with the side length of 50 mm was used for analysis. The density of points in the reference field was 254 dpi. The fractal dimension $\hat{D} = 1.88$ was determined for the surface, the basic statistical information of the surface is: minimum height $z_{\text{min}} = -3.118$ mm and maximum height $z_{\text{max}} = 3.375$ mm. The histogram of the height distribution is shown in figure 3. An example cross section through the reference surface is shown in figure 4.

Fig. 3. Histogram of $z$ values, on a frequency of occurrence scale
Figure 4. Height profile $z$ [mm]: a) base model generated artificial surface ($s = 1 \text{mm}^2$ and $r = 10 \text{ mm}$), b) measured by laser profilometer concrete surface (described by spherical model with parameters $s = 0.5 \text{ mm}^2$ and $r = 18 \text{ mm}$)

Figure 5 shows the relationship between the sampling density in the range [2.54, 254.] dpi, and the fractal dimension of the task. The absolute error of the measured values was assumed to be a constant value of 0.1 mm. Fractal dimension values were obtained for the profiles after applying a moving average in the range 1.2 to 1.4.

Figure 5. Fractal dimension of the profile depending on the resolution of the measurement device (the result are for 20 different cross sections from tested surface)

Figure 6 shows the relationships of the recovered surface parameters from the tests with profilometers of different resolutions, the results are shown on a semi-logarithmic scale. The trend is slightly increasing for the variation (sill) and also slightly decreasing for the threshold (range) of the spherical model. Figure 7 shows the variation of the surface parameters recovered from the profiles as a function of the measurement error. It can be noted that there is a significant proportional increase in the determination error of the variation parameter (sill) in the spherical model from the error of the measuring device and stabilization of the threshold (range) of the model for the error above 0.5 mm.
The paper [6] indicates a strong relationship between the sill parameter and the cohesion between the layers of old and new concrete. Thus, the correct determination of contact parameters is linked to obtain the planned load bearing capacity of the joint. By analyzing the summary in Table 2 and the test results, it is possible to choose the sensor type HG-C1100 as the optimum sensor with respect to measuring range and acceptable error value. The influence of the length of the path tested with the profilometer on the result of the reconstruction of geostatic model parameters was not investigated in this paper.

![Figure 6](image)

**Figure 6.** The relationships of the recovered surface parameters from the tests with profilometers of different length resolutions (semi-logarithmic scale) for spherical model: a) sill parameter; b) range parameter

For the purpose of measuring and reconstructing the concrete surface using the geostatistical model, under the assumptions presented in this paper, the measuring equipment should be selected with the basic criterion of the accuracy of determining the height of the sample, the optimal solution seems to be a device with a measurement error of 0.1 to 0.3 mm.

![Figure 7](image)

**Figure 7.** The relationships of the recovered surface parameters from the tests with profilometers of different height resolutions (semi-logarithmic scale) for spherical model: a) sill parameter; b) range parameter

4. **Conclusions**

The possibility of detection of surface parameters based on the performed two-dimensional profiles was numerically investigated. The quality of the surface model parameters estimation depends mainly on the accuracy of determining the height of points of the examined profile from the average level (from 100 - 200% of their values). The results of fitting are not significantly influenced by the density of sampling along the profile. There was no influence of self-repeatability (measured by fractal
dimension), on estimated parameters. An important consideration in the selection of a laser device is the measurement range, it affects the accuracy of the measurement and, of course, the possibility of texture measurement. A compromise is necessary and determined by the expected high variability of the surface to be measured.

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