

# Reliability of Percussion Drilling as a Mean to Define Rock Surface

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**Abstract.** In Finnish ground investigation methods percussion drilling has an important role as a mean to define the rock surface. Ground conditions in Finland vary a lot, however, it is quite common that the soil layers are relatively thin and the rock surface lies in around 3...5 meters depth. Besides that the rock is usually very hard, so it has to be blasted away in many cases. Not only is blasting much more expensive than excavation, the level of rock also often determines the foundation depth and the design solutions. Therefore, the knowledge of rock surface is essential before construction work starts. Based on the pointwise ground investigations, like percussion drillings and measurements, the rock surface is normally modeled as three dimensional soil surface in design programs, where the surface geometry is described as triangulated irregular network (TIN). Geotechnical solutions, and the calculation of costs and quantities are often based on this model and thus, it should be as accurate as possible. The aim of this study is to analyze how reliably the rock surface can be modeled with percussion drillings, and also how the density of drillings affects the reliability. The study will be based on the statistical data from four Finnish construction sites, situating in different parts of Finland. Monte Carlo method is implemented in the statistical studies to define the effect of the amount of drillings. The goal is to determine proper drilling densities for different situations. The analysis includes the measurement errors and variability of the ground conditions. The results are studied in terms of relative volume differences, which is useful indicator in quantity calculations. Based on the results, percussion drilling grid density of about 15 m x 15 m provides a sufficient estimate of rock surface profile in most cases. If more accurate results are needed, drilling density should be adopted appropriately.

**Keywords.** Percussion drilling, rock surface model, Monte Carlo method, building information model

## 1. Introduction

According to common conception, the largest uncertainties in a construction project usually lie in the ground survey data. Ground conditions are typically heterogeneous, and local scattering is often considerable. While it is impossible to investigate the whole soil profile in construction area, simplified geological surface models are created based on the pointwise site investigation results. Reliability of such models is affected by the inaccuracies in the site investigation methods, and the density of the investigations.

It is often very challenging to estimate the proper investigation amount due to heterogeneity in ground conditions. In general, the designers wish to have more investigations, but typically the amount depends on how much resources client or the project manager are willing to invest. (Jaksa et al. 2005.)

The Finnish bedrock is part of the oldest bedrock areas in Eurasia, with an age of around 3000–1500 million years (Lehtinen et al. 1998). The depth of bedrock in Finland varies from 0 to more than 100 meters, with an average of about ten meters. According to Jääskeläinen (2011), about 13,4 % of the Finnish surface area is either exposed rock or covered with very thin soil layers. In fact, compared to most other countries, the thickness of soil layers covering the bedrock in Finland is in general relatively small. Therefore, the knowledge of the bedrock surface location is essential in designing infrastructures in Finland. This knowledge is used in selection of foundation method, drilling pile length estimation, designing of road cross-sections, quantity and cost calculations, and naturally in the design of tunnels or other underground spaces (Finnish Transport Agency 2011).

An important aspect today is the on-going transition process from traditional design methods towards building information models. Use of building information models emphasizes the importance of reliable site investigation data (Liukas & Virtanen 2014). Estimated rock levels acquired from percussion drillings are usually the core information in creation of rock surface model.

Percussion drilling is the most commonly used site investigation for defining the level of bedrock. The drilling method is described in Finnish Geotechnical Society's (SGY) survey guidelines (1986). The bedrock surface can be determined from the resistance differences between granular soil and rock. Percussion drilling is considered relatively reliable method in Finnish geological conditions (Finnish Transport Agency 2011).

The aim of this study was to estimate the reliability of the modelled rock surface. The reliability was reflected to the amount of the percussion drillings in order to estimate proper amount for the drillings. Secondary aims were to evaluate how drillings' different error distributions and different geological conditions affected the results.

## 2. Materials and Methods

### 2.1. Ground Investigation Data

The research material consisted of estimated rock levels acquired from site investigations and the real rock levels measured from exposed bedrock surface. The data was obtained from four real construction sites in Finland (Table 1), three of which were infraconstruction sites and one was a metro station. Percussion drilling results, aka the estimated rock levels, were compared to the measured bedrock levels in each site. Therefore, only those percussion drillings, which located in areas where the rock levels were measured, could be utilized in this study. The coordinates of both estimated and measured bedrock levels were collected in database.

### 2.2. Analysis Methods

The analysis was done in two parts. In the first part, by comparing the estimated rock level data to the "real" measured bedrock level data, the average errors of percussion drillings and their standard deviations were defined separately for each site. These error distributions were used as input data for Monte Carlo simulations in the second part of the analysis. The aim of the Monte Carlo simulations was to determine the effect of drilling density to the reliability of the estimated rock surface model. Reliability was measured in terms of volume differences between measured and estimated rock surface models, and the effect of percussion drilling density on results was evaluated.

**Table 1.** Construction sites and amount of drillings.

Site	Number of percussion drillings	Number of utilized drillings
<i>Koloko</i> (Highway 7)	3371	1046
<i>Sepänkylä</i> (Highway 8)	382	102
<i>Ring 3</i> (Highway 50)	619	56
<i>Urheilupuisto</i> (Metro station)	118	32

### 3. Definition of Testing Error Distribution for Percussion Drillings

All the data used in the study was in form of coordinate points, and it was transferred into the computational program (MATLAB) as lists of coordinates.

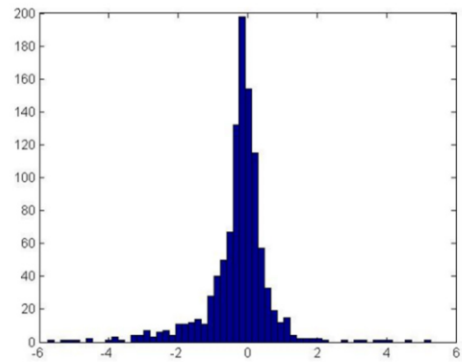
The testing errors for the percussion drillings can be calculated by simply subtracting the real rock levels from the estimated rock levels acquired from the drillings. However, since the real rock levels in MATLAB were in form of measurement points rather than as a continuous surface model, rock level at the location of each percussion drilling had to be calculated first. For a single drilling, this was done linearly from three closest measurement points that form a triangle around the drilling location. The accuracy of this method was checked manually,

and it proved to be functioning. The differences between the estimated and real rock levels were calculated, and the means and standard deviations of the results were calculated separately for each individual site. These statistics define the testing error distributions in percussion drillings for each site. The results are shown in Table 2. Graphical illustrations of the distributions of errors were also created as histograms. An example of such histogram from one site (*Koloko*) is presented in Figure 1. It should be noted that since the real rock surface levels were subtracted from the estimated levels, negative value in Table 2 and Figure 1 express that the real rock surface was higher than the estimated level.

**Table 2.** Testing errors for construction sites.

Site	Number of drillings	Mean (m)	Standard deviation (m)
<i>Koloko</i> (Highway 7)	1046	-0.230	0.899
<i>Sepänkylä</i> (Highway 8)	102	-0.465	0.999
<i>Ring 3</i> (Highway 50)	56	0.048	0.296
<i>Urheilupuisto</i> (Metro station)	32	0.420	1.360

As can be seen from Table 2, the testing error distributions are very site dependent. Percussion drillings in *Ring 3* have been quite successful: the estimated rock surface level was on average less than 0.05 (0.048) meters wrong, with a standard deviation of 0.296 meters. On the other hand, the average testing errors in percussion drillings for *Sepänkylä* and *Urheilupuisto* are more than 0.4 meters, and rather confusingly in different directions as well (-0.465 for *Sepänkylä* and 0.420 for *Urheilupuisto*). The standard deviations of the errors are also quite large in these sites. Average testing error for percussion drillings in site 1 (*Koloko*) is -0.230 meter, with standard deviation of 0.899 meters. These results were used as initial data for the second part of the analysis.



**Figure 1.** Histogram of Koloko percussion drilling errors.

Table 2 shows also, that site *Koloko* contains by far the largest amount of data. In fact, it is the only one where the amount of data can really be considered sufficient for statistical analyses.

#### 4. Reliability of Rock Surface Model in Terms of Volume Differences

The framework for the second part of the analysis is presented in flowchart form in Figure 2. The first step was to choose several (in this case 5) zones of measured bedrock, and simulate grids of percussion drillings upon them. In order to be able to evaluate the influence of different geological environments (spatial variation in rock surface), the topography of the rock surfaces in the chosen zones were purposely as various as possible. For instance, zone 2 had the least variation in rock surface topography (very even surface), while zone 5 had the most. Drilling grids were simulated in the zones with randomness in their xy-plane location. The z coordinates set for the simulated drilling points were pseudorandom so that their error distribution matched testing errors defined in the first part of the analysis. The testing errors were assumed to be normally distributed, which is a common assumption in the traditional error theory (Honjo 2011). The z coordinates for simulated percussion drillings were calculated from the measured rock surface levels as follows:

$$Z_{\text{est}} = Z_{\text{meas}} + \text{randn} \times s_x + \bar{x} \quad (1)$$

in which  $z_{est}$  is the estimated rock level acquired from a simulated drilling,  $z_{meas}$  is the measured rock level at the location of the drilling,  $randn$  is a random value from normal distribution,  $s_x$  is the standard deviation of the error and  $\bar{x}$  is the average error defined in the first part of the analysis.

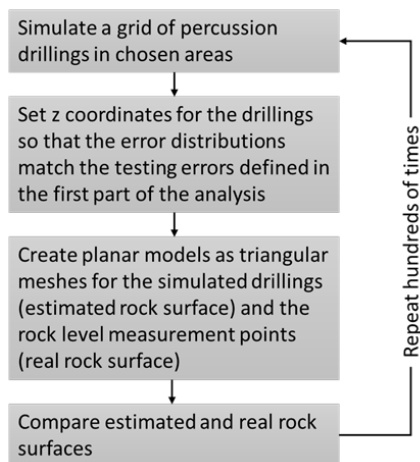


Figure 2. Calculation flowchart.

After producing the grids of simulated percussion drillings, separate triangular irregular network models were generated for both the simulated drillings and the measurement points. These models represent estimated rock surface and real rock surface respectively, and they were compared in terms of volume differences. Volumes were calculated for both surfaces from sea level ( $z = 0$ ), and the volume of real rock surface was subtracted from the volume of estimated rock surface. Since different zones varied in size, it was more relevant to study relative volume differences instead of their absolute values. Therefore, the resulting volume differences were divided with the corresponding surface model areas (same for both surfaces). Hence, the function for relative volume differences are calculated as follows:

$$\Delta V_{rel} = \frac{V_{est} - V_{meas}}{A} \quad (2)$$

in which  $\Delta V_{rel}$  is the relative volume difference [ $m^3/m^2$ ],  $V_{est}$  is the volume between estimated rock surface and sea level ( $z = 0$ ) [ $m^3$ ],  $V_{meas}$  is the volume between real rock surface

and sea level [ $m^3$ ], and  $A$  is the area of the corresponding surface models [ $m^2$ ] (same for both surfaces).

This whole simulation process was repeated hundreds of times in accordance with Monte Carlo method. Sufficient number of simulations was determined with a 1000 repetition test run. As can be seen from Figures 3 and 4, the results were quite stabilized after 500 simulations. Thus, the number of simulations set for the calculations was 500. The relative volume difference results were collected in  $n$ -by- $z$  sized matrix, in which  $n$  is the number of simulations and the  $z$  is the number of zones. Means and standard deviations were calculated from the results separately for each zone. For every error distribution defined in the first part of the analysis, six individual runs were performed with different simulated percussion drilling grid sizes. Grids were always simulated in square formations, and used grid sizes were 5, 10, 15, 20, 25 and 30 meters.

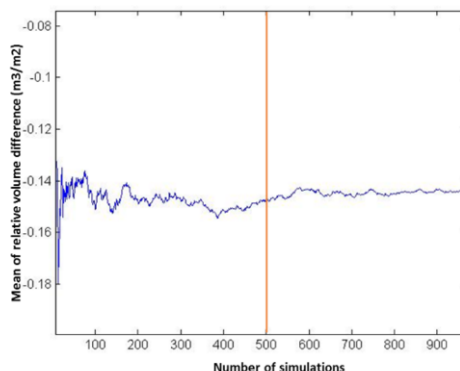


Figure 3. The progress of mean relative volume difference in 1000 repetition test run

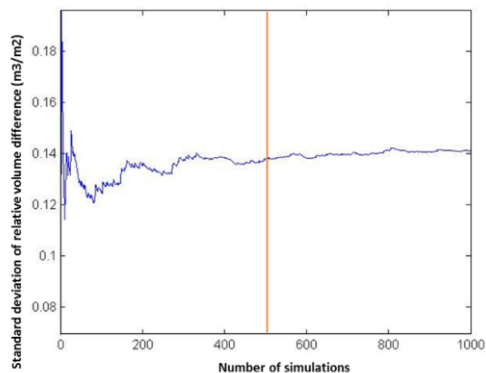


Figure 4. The progress of standard deviation of relative volume difference in 1000 repetition test run

5. Results

The means and standard deviations of relative volume differences as a function of drilling

density for different zones are presented in Figures 5 and 6. These results were calculated with error distribution of site 1, *Koloko*.

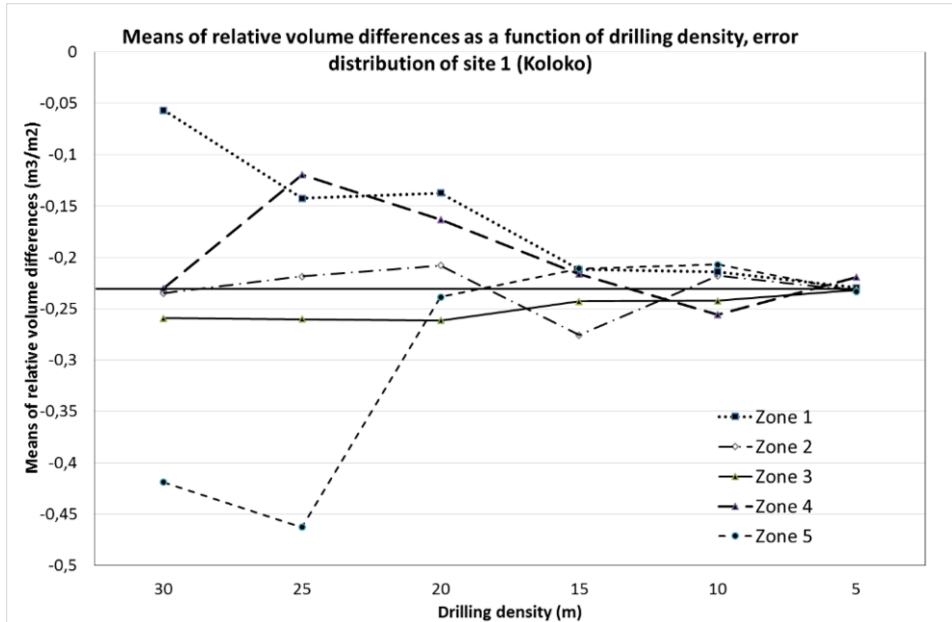


Figure 5. Means of relative volume differences

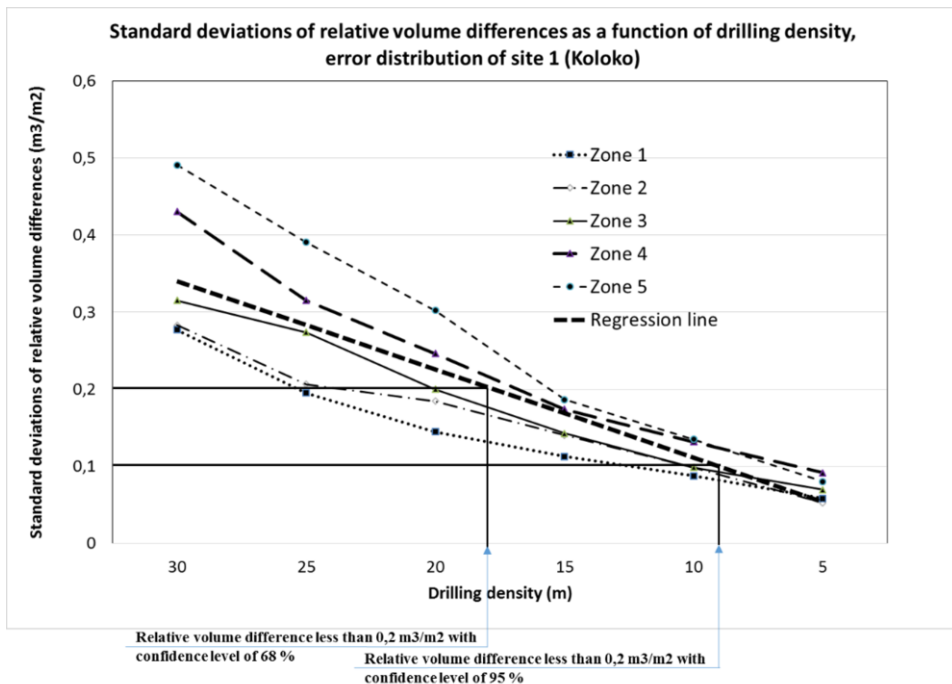


Figure 6. Standard deviations of relative volume differences

Figure 5 shows that the mean relative volume differences vary immensely between zones when the drilling density is sparse. However, as the drilling density increases, the variance in means decreases, and starts to be already quite leveled out in all zones at drilling density of 15 meters. As the drilling density increases further, the means eventually approach one value. As expected, this value is the same as the mean percussion drilling testing error utilized in this calculation (horizontal line in Figure 5, -0.230 meters). As a side note, it was also noticed that the zones where denser drilling grids affected means the most (zones 1 and 5) were the ones with most variability in the rock level topography.

The standard deviations in Figure 6 express how much the result of a single simulation differs on average from the mean result calculated from 500 simulations. As expected, the standard deviations decrease almost linearly as the drilling density increases. Since the relative volume difference results are assumed to be normally distributed, it is possible to exploit characteristics of a normal distribution in result evaluation. For instance, let's say we want to estimate such drilling density, where the result of a single simulation and the mean result from hundreds of simulations do not differ more than  $0.2 \text{ m}^3/\text{m}^2$  at 95 % confidence level. The result for this can be estimated from Figure 6 by seeking a drilling density value where the regression line crosses the standard deviation value of  $0.1 \text{ m}^3/\text{m}^2$  ( $0.2/2 \text{ m}^3/\text{m}^2$ ). Regression line is used, since it represents a coarse estimation of the results in an average geological environment. The resulting drilling density estimated from Figure 6 is hereby approximately 9 meters (grid size 9 m x 9 m). This result is quite dependable on the error distribution set for the simulations. For instance, equivalent drilling density values are 15 meters for site *Ring 3*'s error distribution, and 8 meters for site *Sepänkylä*'s error distribution. If lower confidence level is enough, more sparse drilling density can be adequate.

## 6. Conclusions

Percussion drillings' testing error distributions calculated in the first part of the analysis were quite dissimilar on different sites. There are many possible reasons for testing errors, for instance difficult geological conditions, spatial variation, improper testing equipment and human errors. Thus, estimated rock levels defined from percussion drillings should be treated with certain amount of cautiousness.

Second part of the analysis utilized the error distributions defined for different sites as an input for Monte Carlo simulations. Simulations focused on relative volume differences between estimated and real rock surface models. Volume differences express how accurately for instance the quantities of rock that has to be blasted away can be calculated from estimated rock level model. Thus, volume differences are interesting characteristic for quantity calculations. Results showed that the volume differences were quite dependent on testing error distributions, and the spatial variability in rock surface topography in different zones. However, as the drilling density increased the results leveled out considerably. Drilling grid size of about 15 m x 15 m was considered to be relatively good general percussion drilling density for quantity calculations. If more (or less) accurate calculations are required, or the rock levels defined from percussion drilling hold extra uncertainty (or certainty), drilling density should be adopted adequately.

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