Application of High- and Low-Pass Spatial Filters in Analysis of Cone Penetration Test (CPTu)

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Abstract. The paper examines the high and low pass spatial filters used in the Cone Penetration Test (CPT) recordings in the soil and aims to demonstrate their usefulness and effectiveness in the interpretation of CPT measurements. The procedure of low-pass inverse filtration was used to reduce the effects associated with the occurrence of thin layers. High-pass filters were used to find places where the boundary of layers between different Soil Behaviour Type (SBT) could potentially exist. The application of both filters was tested on natural soils and on anthropological dumping soils.

1. Introduction

CPTu static sounding is one of the in-situ testing methods used in geotechnics to test soil properties. The first soundings were performed in 1932 in the Netherlands. Since then, the method has been constantly developed, and its range of applications has been extended [1]. Due to its high speed and simplicity, it is currently one of the most popular in-situ soil testing methods. Its results may be used among other things to identify strata boundaries in the geological profile. Based on empirical relationships and correlations, the results may serve to define almost all strength and mechanical parameters of the soil.

Figure 1. Examples of failure mechanisms in the limit equilibrium state according to De Beer theory [2].
As the electric cone tip penetrates into the ground at a constant speed (2 cm/s), three values are recorded as a rule: \( q_c \) cone penetration, \( f_s \) sleeve friction and \( u_2 \) pore pressure. Although static CPTu probing provides extensive information which can be used in estimating soil properties in the profile, the measurement at a particular point is influenced by the surroundings, i.e. by the spatial arrangement of the layers surrounding the cone [3, 4]. In the case when the measurements are performed in a stratified and anthropogenic ground, the obtained recordings contain values characteristic not only of individual homogeneous layers of natural ground, but also of the influence of individual interbeddings and interlayer (transition) zones [5]. This fact can be explained by an analogy and comparison between the operation of a CPTu cone and a foundation pile in the limit state (Fig. 1). In the figure below, the glide lines around the cone pass through the layers both above and below the actual position of the cone.

This research focuses on testing high- and low-pass spatial filters applied in recordings of CPTu soundings and aims at demonstrating their usage potential and effectiveness in interpretations of measurements which consist in separating geotechnical layers in an investigated ground profile, as this could help improve the quality of these interpretations.

2. Study of CPTu record filtering

The measurement characteristics \( q_c \) and \( f_s \) depend on the sequence and the properties of all of the ground layers surrounding the cone and located in the zone influenced by the pushed (driven) cone. Soils surrounding the cone at a distance of up to approx. 10-30 cone diameters have a particularly significant influence on the measurement results. This distance corresponds to approx. 0.35 m – 1.3 m for a standard cone whose surface area of the base is 10 cm² and the surface area of the friction sleeve is 150 m². Over the previous years, very intensive research has been performed into the effects of ground stratification, thin interbeddings formed by layers of a different ground in the measurement profile, and transition zones between various ground layers [6]. Boulanger and DeJong [5] offer a review and a summary of the research performed so far in the field.

![Figure 2. Schematic diagram of thin layer effect for sand embedded in clay [5].](image)

Figure 2 shows cases of strong soil layers having various thicknesses and located in weak soil in order to illustrate the effects of both the thin layer and the transition zone between the layers. The measured resistance under the cone tip is marked as \( q^m \). The measured cone resistance fluently rises as the cone approaches and enters the stronger layer, and then fluently decreases as the cone approaches and enters the weaker layer. The “true” tip resistance (marked as \( q^t \)) is a hypothetical value which would
be recorded in these soils if the measurement was free from the influence of the weak ground above and below, i.e. without the interbedding (profile 1 for weak soil and profile 2 for strong soil). The term transition zones here used should refer to sections in the vicinity of layer boundaries, in which \( q_m \) fluently increases or decreases despite rapid changes \( q_t \). The thin layer effect occurs when the peak \( q_m \) is smaller than the corresponding \( q_t \). The case analyzed in the graphs allows an observation that the thinner the interbeddings, the greater the error value (the difference between \( q_m \) and \( q_t \)). This error is evaluated by introducing thin layer factor \( K_h \), which is defined as a relationship between \( q_t \) and the maximum recording \( q_m \) for a particular layer (Figure 2).

Lune et al. [1] presented a solution based on the simplified elastic solution developed by Vreugdenhil, which provides some information on the correction of cone recordings for thin layers. The publication demonstrated that the measurement error is the function of layer thickness and relative layer stiffness. Relative layer stiffness is reflected in the relationship between the cone resistance in the interbedding and the cone recording in the surrounding ground. Based on this solution, the “true” cone tip resistance is described as:

\[
q_t = K_c \cdot q_m
\]  

where \( K_c \) is corrective factor of cone resistance.

The above technique is justified in the case of natural soils, with additional information available on particular grounds and their thicknesses, as read from the profile of a drill hole. In contrast, the low- and high-pass spatial filtering techniques presented below are not constrained by this limitation.

2.1. Inverse low-pass spatial filtering procedure

A different approach to the problem of stratification in CPTu soundings has been offered by Boulander and DeJong [5]. These authors suggest that a cone penetrometer acts as a low-pass spatial filter and that therefore a “true” measurement can be obtained by following the inverse filtering procedure. Low-pass spatial filters and inverse filtering are commonly used in image and signal processing. Low-pass filters are also referred to as “blurring” or “smoothing” filters and allow the averaging of sudden intensity changes (Figure 3). The simplest low-pass filter calculates an average from one pixel by using its immediately neighboring pixels. The result of this operation replaces the original pixel value. This procedure is repeated for each successive recording in the profile. As a result, slight noises can be removed from the recording, the image can be smoothened and the edges can be blurred. In terms of statistics, it can be said that a low-pass filter works like a moving average. The inverse filtering technique may help to restore or improve image (measurement) quality, if it is possible to develop a model of the function which had “blurred” (deformed) the measurement and if the relationship between the signal and the noise is favourable.

![Figure 3. Image before and after using low-pass spatial filter.](image-url)
Application of inverse filtering techniques to data obtained from cone penetration tests starts with an assumption that a “true” cone penetration resistance \( q_t \) exists which would be obtained if the value of the recording depended solely on the soil properties at a particular point. However, the recorded cone penetration resistance \( q_m \) depends on the properties of the grounds in the impact zone not only at the point, but also in the surroundings of the cone tip (analogy to the base of a foundation or a pile in limit state \([8, 9]\)), so that cone penetration can be compared to a low-pass spatial filter applied to the “true” recorded profile \( q' \) (Figures 3 and 4). The effect produced by filtering the cone resistance can be expressed as:

\[
q^m(z) = q'(z) \ast w_c(z)
\]  

where:
- \( q^m \) – measurement recorded during the penetration test (\( q_c \));
- \( q' \) – “true” measurement, if the recording was free from the impact of:
  - the neighboring soil medium located both above and below the cone,
  - other factors, e.g. those related to the penetration speed of the cone, to atmospheric pressure etc.;
- \( w_c \) – cone penetration filter.

The asterisk in relationship (3) indicates a convolution of functions \( q' \) and \( w_c \). As an alternative, the result may be expressed as:

\[
q_c^m(z) = \int_{z-\Delta z_{\text{min}}}^{z+\Delta z_{\text{max}}} q'(\tau)w_c(z-\tau)d\tau
\]

The inverse filtering process is complicated mainly due to the strongly non-linear nature of \( w_c \). In addition, calculating this function is very difficult without full information on the thicknesses of successive layers and the characteristic values of “true” \( q' \) inside the penetrated layers. Including a great number of various factors is a challenge, especially in the case of measurements performed with the use of various types of cones. Studies of the literature indicate that in the case of a CPTu sounding, the filtering functions \( w_c \) are more typically closer to lognormal distribution than to normal distribution \([5]\). Such inverse filtering is intended to highlight atypical measurements and to polarization the recording – reversely to what low-pass spatial filters do.

The procedure proposed in \([5]\) can be divided into three basic stages:

1. Defining low pass filter model for the cone \( w_c \).
2. Performing the procedure of iterative solving the problem in order to estimate the “true” cone penetration resistance \( q' \) on the basis of the recorded cone penetration resistance \( q^m \) and the filter model for cone penetration \( w_c \).
3. Performing a procedure aimed at identifying sharp transition zones between ground layers and at improving the data for those zones.
2.2. High-pass filtering procedure

Based on an observation in [10], which states that the CPTu values can be viewed as a signal and processed similarly to sound or image, a high-pass spatial filter can be applied to CPTu recordings.

This filter may be used to obtain a sharper image or to highlight some elements of the image. This filter type exposes fine details – reversely to what low-pass spatial filters do. They are frequently used to detect edges in images (Figures 5 and 8). An edge is a rapid change of intensity and in Figure 6 it can be seen at point \( x_0 \).

In fact, an intensity change never has a shape as demonstrated in the above figure. A transition zone is always present, which may be linear or non-linear, as in Figure 7.

In the case of CPTu recordings, the application of high-pass filters allows the layer boundaries (edges) to become more visible, and subsequently, with the individual layers exposed, allows a more detailed variability analysis with regard to actual stratification.

One of the basic high-pass filters is the filter based on the Laplace operator. The Laplacian is a differential operator of the second order, having the following form in the two-dimensional Cartesian coordinate system:

\[
\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}
\]  

(4)
In the filter, the edge (the inter-layer boundary) is assumed to be located at a point of the greatest recorded intensity change, which corresponds to maximum gradient values and typically results in the Laplacian being zero. In a one-dimensional space, the Laplacian corresponds (5) to the second derivative of the investigated function. In the case of CPTu measurements, which are discrete along one line, this can be approximated with the use of the finite difference method.

\[ \Delta f(x) = \frac{f(x + h) - 2f(x) + f(x - h)}{h^2} \]  

(5)

where:

- \( f(x) \) – discrete function describing a CPTu recording (e.g. \( q_c \));
- \( h \) – vertical distance between the neighbouring measurements.

High pass filtration is distinguished from low pass filtration by the fact that in the case of high pass filters the result is expressed in a different unit than the records, which was not the case with low pass filtration. This fact results directly from the use of the finite difference formula (6), where in the denominator there is a division by the square of the distance between individual records.

Figure 8. Before and after using the Laplacian-based filter.

Figure 8 shows the Laplacian-based filter in operation on the image. In the figure, images a) and c) in the left column contain filtered images. Images b) and d) on the right show the filtering effect. The images in the upper row represent the filtering effect on the original image without any additional image processing. In the bottom row, the source image was already processed with a low-pass filter. In both situations, the high-pass filter was able to indicate the edges and contours of the images. This example demonstrates that even if the CPTu measurement is viewed as an image processed with a low-pass spatial filter, in accordance with the suggestions contained in [5], a high-pass filter will be still able to identify its “edges,” which correspond to layer boundaries in the investigated soil.
3. Filtering results in natural soil and in anthropogenic soil

Tests of the above-described techniques were performed on the basis of two CPTu profiles in natural soils (A1 and A2 described in the paper [12]) and two CPTu profiles in anthropogenic dump soils (B1 and B2 described in the paper [13, 14]).

Based on the observation that the $w_c$ filter described in [5] paper is usually of a shape similar to normal or lognormal distribution, the paper adopts deterministically its own $w_c$ filter, where the weight value is only affected by the distance from registration and described using lognormal and normal distribution (Figure 9).

![Figure 9](image)

**Figure 9.** Weights used in reverse data filtering with the use of a) normal distribution; b) lognormal distribution.

During the inverse filtering of recording $q_m$, for normal distribution the filter range included four measurements above and four measurements below a particular recording at depth $z_i$, i.e. a range of 8 cm above and below the recording location (Figure 9a). During the reverse filtering based on lognormal distribution, the range included two recordings above and six recordings below the measurement depth $z_i$. This corresponded to 4 cm above and 12 cm below depth $z_i$ (Figure 9b). This inverse filtering range was dictated by literature studies, which indicate that the range should depend on the size of the cone [5].

Variability analysis was performed independently for 4 types of data:

- The first type includes the measured recordings $q_i$;
- The second type is the result of the performed inverse filtering procedure (filter $w_c$ based on the normal distribution);
- The third type is the result of the performed inverse filtering procedure (filter $w_c$ based on the lognormal distribution);
- The fourth type are original recordings after the application of the high-pass spatial filter.
4. Discussion of results

Figure 10 shows examples of $q_c$ recordings with graphs after filtering. The original record is shown in red (on each of the charts), which was a reference point showing how the above mentioned filters work. Blue and pink are the recordings after inverse filtering using both of the above mentioned $w_c$ filters (with normal and lognormal distribution).

On the profile Fig.10a) in the natural soil A1 at a depth of about 8m it can be seen that on the original recordings $q_m$ ($q_c$) there is a certain smooth stroke in the value of $q_c$ on a small range of depth. At this point it is possible to see how well the inverse filtration procedure works. Namely, it multiplies the increase in the $q_c$ recording on the result of the thin layer and transition zones increasing the recording value in the thin layer. This shows that the low-pass inverse filtering procedure can work as an alternative to the $K_c$ correction factor described in [1]. It also means that there are no thin layers outside this one place in the profiles. In the other $q_c$ resistance records (for A1 and A2), there are no clear differences between the original record and the one after inverse filtering. On the Fig.10c) and d) recordings for the anthropogenic dumping soil, the inverse filtering effect is disappearing, which may
indicate that the soil is globally homogenous or that there are no noticeable strong boundaries between the components.

After applying a high pass filter, most of the records oscillate around zero, but there are impulses that reach values several rows higher than other values. At the peaks, it is possible to assume that there are edges - boundaries of individual SBT layers, because in the "vicinity" of the edges, the laplasian reaches extreme values. In natural soils, the peaks are much more valuable and differ more from other records than in dumping soils. For natural soils in Fig. 10a) and b) the axis concerning the recording after high-pass filtering has values higher by a row than in case of the recording in Fig. 10c) and 10d) connected with dumping soils. Additionally, the number of peaks in dumping soils is definitely higher than in the case of natural soils, which may mean that the geological profile contains such a large number of heterogeneities that, globally, it may be considered as a homogenous medium.

It can be also noticed that the above described pulses appear on the recordings after high-pass filtering in places where the recordings after inverse filtering deviate noticeably from the original one. This means that both filters are compatible with each other.

5. Conclusions
The presented filtering procedures allow the recorded results to be polarized and the weaker layers to be easily identified. After the identification criterion for the type of soil is chosen and the ground layer identification is properly calibrated, high-pass spatial filtering may prove useful as a tool which helps to identify the boundaries between the components identified in the CPTu profile.

It may be interesting to further test a case in which high-pass filtering would be preceded not by reverse filtering but by low-pass filtering, e.g. in accordance with normal distribution. In such case, the measurement subjected to preliminary smoothing would not contain so strong local peaks in minimum and maximum recordings, which could be caused e.g. when the penetration cone hits a small rock. Filtered recordings would not contain sudden peaks, which a sensitive high-pass filter misinterprets as layer boundaries.

Recordings subjected to inverse filtering demonstrate much greater variability. In the analyzed example of the dump soil profiles, the reverse filtering procedure did not introduce any significant information to the solution. High-pass filtering, which detects local weaker layers, provides definitely better results.

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