

Method and device for determining a geotechnical parameter of an excavated material

The invention relates to a method for determining at least one geotechnical parameter of an excavated material of a tunnel boring machine.

The type and composition of the excavated material from tunnel boring machines (TBMs) is dependent, of course, on the composition of the ground formation (rock or soil) present at the working face, and additionally also on the type of the driving and the materials added in this case to the excavated material.

In soft, cohesive soil, excavation machines having earth pressure support are preferably used, so-called earth pressure balance shield tunnel boring machines. In the case of the earth pressure balance shields, a slurry made up of excavated material and water is used as a plastic support medium. A tool-equipped, rotating cutting wheel of the TBM is pressed against the working face and loosens the soil present. This excavated material reaches the excavation chamber via openings, where it mixes with already present slurry. A conveyor screw transports the excavated material from the bottom of the excavation chamber to a conveyor belt. The support pressure of the slurry can be controlled precisely in this case by the interplay of conveyor rate of the conveyor screw and driving speed. The pressure conditions are continuously monitored by means of earth pressure sensors in the excavation chamber. Therefore, all driving parameters can be adapted optimally to one another by the machine driver even in the case of changing geological conditions. This enables the required compensation for the pressure conditions at the working face, prevents uncontrolled penetration of the soil into the part of the tunnel boring machine under atmospheric pressure, and thus provides the condition for rapid advance with little settling.

Not all soil available in the natural state has ideal properties for an earth pressure balance shield drive. However, the range of application of the method can be expanded by soil conditioning. In this case, plastic deformability, consistency, and water permeability of the geology are changed by adding various conditioning agents, such as water, clay, or foam. Earth pressure balance shields can thus also achieve good advance performances in heterogeneous soils having variable proportions of gravel, sand, or water or in unstable ground formations.

However, if too much water, clay, and/or foam is admixed to the excavated material, the excavated material transported, for example, by the conveyor screw onto the conveyor belt can be deposited poorly due to a free-flowing consistency; for example, it has to be temporarily stored in trenches or settling basins or further treated. This possibly results in increased costs. In

addition, there is often the specification for the use of landfills that a minimum shear strength of the excavated material to be landfilled cannot fall below 10 kN/m².

In such applications and further applications, it is therefore desirable to determine geotechnical, in particular rheological parameters of the excavated material conveyed out of the excavation chamber, such as viscosity and yield point, the (vane) shear strength or the slump (according to DIN EN 12350-2), in running operation. For example, the determination of the slump (according to DIN EN 12350-2) requires taking a sample from the conveyor flow and – in the context of a slump test – filling a metal mold of predetermined dimensions in the shape of a truncated cone, lifting off the metal mold in a defined manner, and measuring the difference between metal mold height and the height of the excavated material truncated cone which has collapsed after the lifting off. This takes time and cannot be completely automated; in particular, a continuous measured value capture is not possible. This applies similarly to the determination of alternative geotechnical parameters, such as the flow spread, the vane shear strength, or the dynamic viscosity and the yield point.

The object of the invention is therefore to determine in an automated manner geotechnical parameters of the excavated material conveyed out of the excavation chamber in running operation.

This object is achieved according to the invention by a method for determining at least one geotechnical parameter of an excavated material of a tunnel boring machine having the features of claim 1 and by a device for determining at least one geotechnical parameter of an excavated material arising in a tunnel boring machine having the features of claim 14.

The at least one geotechnical parameter is preferably determined in an automated manner.

In the method according to the invention for determining at least one geotechnical parameter of an excavated material of a tunnel boring machine, the excavated material is deposited on a conveyor device for transporting the excavated material. An impact body is arranged in a conveyor flow of the excavated material in such a way that it plunges at least partially into the excavated material, wherein the excavated material in the conveyor flow has a flow speed which is either specified or measured. A measured variable which corresponds to a force exerted by the excavated material of the conveyor flow on the impact body is then measured, wherein a time sequence of measured values of the measured variable is captured, and the at least one geotechnical parameter is determined from a section of the sequence of measured values in that the section of the time sequence of measured values is input into a data processing device and

is processed thereby such that at least one output value corresponding to the at least one geotechnical parameter is output, wherein either the processing of the measured values is based on the specified flow speed or a value for the measured flow speed is input and taken into consideration in the processing of the measured values.

The data processing device preferably implements a trained neural network, which has multiple layers of nodes, wherein all links between the nodes are assigned weights and predetermined activation functions are assigned to the nodes, wherein the weights have been set beforehand by means of a training method. A matrix of input data is obtained from the section of the sequence of measured values and the matrix of input data is input into an input layer of nodes of the neural network. The at least one output value corresponding to the at least one geotechnical parameter is output by at least one node of an output layer of the neural network.

It is advantageous in this case that it is possible to measure directly on the existing conveyor flow and that the desired geotechnical parameter, such as the slump, is automatically provided after a very short data processing time, which enables, for example, the amount(s) added of water and/or foam and/or further additives influencing the rheological properties of the excavated material to be set depending on the determined geotechnical parameter(s) and therefore to be regulated or the excavated material itself to be classified according to the geotechnical parameter.

In one embodiment, the predetermined activation function is, for example, a reLU activation function ($\text{reLU}(x) = \max(0, x)$) or alternatively – as a differentiable approximation of the reLU activation function – the function $f(x) = \ln(1 + e^x)$. The weights are assigned starting values before beginning the training method, preferably small randomly selected starting values, for example uniformly distributed in the interval $(-0.05, 0.05)$ or random numbers normally distributed around the value zero. The training method uses, for example, the square error as a loss function and a gradient descent method for adapting the weights.

In one embodiment of the method for determining at least one geotechnical parameter, the conveyor flow of the excavated material could be guided through a pipe in which the impact body is mounted, for example a rod protruding into the pipe. In one preferred embodiment of the method, however, the impact body is arranged in an open conveyor flow of the excavated material. This is preferably the conveyor flow on a conveyor belt, which is open on top.

In one preferred embodiment of the method for determining at least one geotechnical parameter, a predetermined flow speed of the conveyor flow is set and is kept constant during the capture of the time sequence of measured values of the measured variable. This simplifies the data

processing, since measured value-time pairs do not have to be processed, but rather only measured value sequences. The condition is that the set flow speed is equal to the flow speed which was set when obtaining pairs of measured value sequence and measured geotechnical parameter used in the training method.

The time sequence of measured values is preferably captured at a constant sampling frequency. This also simplifies the data processing, since in this case only a value for the sampling frequency or the time intervals between the measurement points is to be processed or is to be assumed in the processing.

In one preferred embodiment of the method for determining at least one geotechnical parameter, the section of the time sequence of measured values corresponds to a measuring period of 0.25 s to 60 s, preferably of 0.5 s to 1 s. Practical trials using typical compositions and flow speeds of the excavated material have shown that the relevant movement sequences of the impact body essential for determining the geotechnical parameter, in particular the slump, and therefore the essential force profiles to be captured take place within this time interval.

In one embodiment of the method for determining at least one geotechnical parameter, a predetermined number of characteristic features are calculated from the section of the time sequence of measured values and these features are used as the matrix of the input data. For example, mean value, median, maximum value, minimum value, and/or standard deviation or also Fourier coefficients of a discrete Fourier transform are calculated from the section of the time sequence of measured values, also referred to as a measurement sequence, as characteristic features, arranged in a multidimensional matrix, and transferred in scaled form to the input layer.

In another, simple embodiment of the method for determining at least one geotechnical parameter, the section of the time sequence of measured values, the measurement sequence, is used in scaled form as a one-dimensional matrix of the input data.

It is conceivable that the data processing device implements the neural network using special hardware which has a plurality of circuit elements emulating neurons. One preferred embodiment of the method for determining at least one geotechnical parameter is characterized in that, however, the neural network is simulated in a program-controlled manner by the data processing device (so-called artificial neural network). This means that the data processing device executes mathematical operations, which emulate the function of the layers of neurons of a neural network.

Different types of neural networks can be simulated by the data processing device, for example feedforward networks (among other things, multilayer perceptrons), convolutional neural networks, or recurrent neural networks. In one preferred refinement of this method for determining at least one geotechnical parameter, a neural feedforward network having a one-dimensional convolutional neural network is simulated by the data processing device. The amount of computing operations to be executed is significantly reduced in relation to a completely linked network by the use of convolutional neural networks (CNNs). At the same time, neurons in the local vicinity, therefore in the present case measured values of a measurement sequence nearby in time, have a greater influence on the neurons of a following layer.

In a presently preferred exemplary embodiment of the method for determining at least one geotechnical parameter, a convolutional neural network having a first convolution layer having a following pooling layer and a following second convolution layer having multiple following completely linked layers is simulated by the data processing device. It has been shown that using such a design of the neural network, on the one hand, overfitting can be avoided and, on the other hand, good predictions can be achieved.

Preferred embodiments of the method for determining at least one geotechnical parameter are characterized in that before the section of the time sequence of measured values is input to determine the at least one geotechnical parameter, the weights are set in the training method in that

a) for a predetermined selection of a plurality of excavated material samples of different compositions having different geotechnical parameters, in each case:

a1) the at least one geotechnical parameter, for example the slump, of the excavated material sample is measured or determined and stored as a target parameter value,

a2) the impact body is arranged in a conveyor flow of the excavated material sample such that it plunges at least partially into the excavated material, wherein the excavated material in the conveyor flow has a predetermined flow speed, and a measured variable which corresponds to a force exerted by the excavated material of the conveyor flow of the excavated material sample on the impact body is measured, wherein a time sequence of measured values of the measured variable is captured,

a3) pairs each made up of a section of the sequence of measured values are stored in assignment to the target parameter value,

b) starting values are assigned to the weights in the neural network implemented by the data processing device,

c) for a pair made up of a section of the sequence of measured values and assigned target parameter value:

c1) the at least one geotechnical parameter is determined from the section of the sequence of measured values in that the section of the time sequence of measured values is processed by the data processing device implementing the neural network such that at least one output value corresponding to the at least one geotechnical parameter is output,

c2) the difference between the output value and the assigned target parameter value is then determined, and

c3) the weights are changed depending on the difference,

wherein steps c1) to c3) are repeated for a next pair made up of a section of the sequence of measured values and assigned target parameter value, wherein the selection of the pairs takes place in random order,

wherein steps c1) to c3) are executed for a predetermined proportion of the pairs stored in step a), which is used as the training set.

An application of the mentioned method for determining at least one geotechnical parameter is according to the invention a method for setting the consistency of a conditioned excavated material of an earth pressure balance shield tunnel boring machine, in which a conditioning agent, for example a surfactant foam, is admixed with the excavated material for its conditioning in the excavation chamber, the excavated material thus conditioned is conveyed out of the excavation chamber using conveyor devices, wherein at least one geotechnical parameter, preferably a slump, is determined in an automated manner according to one of the above-mentioned methods in an open conveyor flow formed on one of the conveyor devices, and the amount of the conditioning agent to be admixed is regulated depending on the geotechnical parameter thus determined, preferably in that the amount of the conditioning agent to be admixed is increased or reduced depending on the difference between the geotechnical parameter thus determined and a target value of the geotechnical parameter.

An application of the mentioned method for determining at least one geotechnical parameter is according to the invention a method for classifying an excavated material of a tunnel boring machine, wherein the conditioned excavated material is conveyed out of the excavation chamber using at least one conveyor device, wherein at least one geotechnical parameter, preferably a slump, is determined in an automated manner according to one of the above-mentioned methods in an open conveyor flow formed on one of the conveyor devices, and the excavated material is classified depending on the determined geotechnical parameter, in that preferably the excavated material is classified depending on a difference between the geotechnical parameter thus determined and a target value of the geotechnical parameter.

The device according to the invention for determining at least one geotechnical parameter of an excavated material arising in a tunnel boring machine comprises (a) a conveyor device for transporting the excavated material such that a conveyor flow of the excavated material having a flow speed is formed in an open conveyor channel, wherein the conveyor device has a unit for setting a predetermined flow speed and/or a unit for measuring the flow speed, (b) an impact body arranged in the open conveyor channel, which at least partially plunges into the conveyor flow of the excavated material, (c) a measuring device, connected to the impact body, for measuring a measured variable, which corresponds to a force exerted on the impact body by the excavated material of the conveyor flow, (d) a device coupled with the measuring device for capturing sampling values of the measured variable, for converting the sampling values of the measured variable into digital measured values, and for outputting a time sequence of digital measured values, (e) a storage device for temporarily storing the sequence of digital measured values, and (f) a data processing device coupled with the storage device, which is configured so that it processes the section of the sequence of digital measured values and outputs at least one output value corresponding to the at least one geotechnical parameter.

It is advantageous here that the data processing device is configured so that it generates and processes a matrix of input data from the section of the sequence of digital measured values and outputs at least one output value corresponding to the at least one geotechnical parameter and during the processing takes into consideration either the set predetermined flow speed or a measured value of the flow speed, wherein the data processing device implements a trained neural network that has multiple layers of nodes, wherein all linkages between the nodes are assigned weights and predetermined activation functions are assigned to the nodes, wherein the weights have been set beforehand by means of a training method, wherein the matrix of input data is input into an input layer of nodes of the neural network and the at least one output value corresponding to the at least one geotechnical parameter is output at at least one node of an output layer of the neural network.

The impact body can be a body of any form, which is introduced into the conveyor flow of the excavated material such that a force dependent on the rheological properties of the excavated material acts on the impact body. The impact body can preferably be a rod having a round cross section protruding into the conveyor flow. In one preferred exemplary embodiment of the device for determining at least one geotechnical parameter, the impact body is in the form of a ball. Such an impact body has the advantage that it does not have to be arranged in a specific orientation in the flow. A plow-like body is likewise an advantageous embodiment.

In a preferred device for determining at least one geotechnical parameter, the impact body is a steel ball having a weight of 500 g to 2000 g, preferably 800 g to 1000 g. Such a steel ball has, for example, a diameter of approximately 6 cm and a weight of approximately 900 g. A steel ball dimensioned in this way is, at the typical flow speeds (in the range between 1 m/s and 3 m/s) and compositions of the conveyor flow, on the one hand, sufficiently heavy so that it does not excessively "bounce" on the surface of the conveyor flow of the excavated material, but on the other hand is not so heavy that it remains in a constant position nearly uninfluenced by the conveyor flow.

The impact body, for example in the form of a ball, can be mounted on a fixed mount, for example a rod, and protrude into the conveyor flow. For example, a strain gauge of the measuring device can record the force-dependent deflection of such a rod.

In one preferred refinement of the device for determining at least one geotechnical parameter, however, a spherical impact body is fastened on a pivotably suspended rod or a traction cable and a sensor for capturing the measured variable is coupled with the rod or the traction cable, wherein the measured variable corresponds to a traction force absorbed by the rod or the traction cable. Suspending the impact body on a pivotably suspended rod or a traction cable is advantageous because it enables the impact body to evade when it is struck by a relatively large body (for example, a rock) carried along in the excavated material flow.

In one preferred device for determining at least one geotechnical parameter, the data processing device is configured so that it simulates a neural feedforward network in the form of a one-dimensional convolutional neural network. The data processing device is preferably configured here so that it simulates a one-dimensional convolutional neural network having a first convolution layer having a following pooling layer and a following second convolution layer having multiple following completely linked layers. This has the advantages mentioned above in the context of the corresponding preferred embodiment of the method.

Advantageous and/or preferred refinements of the invention are characterized in the dependent claims.

The invention will be described in more detail hereinafter on the basis of a preferred exemplary embodiment shown in the drawings. In the drawings:

Figure 1 shows a schematic sketch of the measuring arrangement of a preferred device for determining at least one geotechnical parameter,

Figure 2 shows an exemplary representation of a measurement series and a section of the measurement series representing a measurement sequence, and

Figure 3 shows a schematic sketch to illustrate the neural network simulated by a data processing device.

Figure 1 schematically shows a rheological measuring arrangement 1 used in the device according to the invention for determining at least one geotechnical parameter, in particular an index parameter such as the slump.

The measuring arrangement 1 is used to determine a geotechnical parameter, such as the slump in particular, in a conveyor flow 3, wherein the conveyor flow 3 moves at a predetermined speed in a conveyor channel 2. The movement of the conveyor flow 3 is indicated by the arrow 4.

For example, the conveyor channel 2 is located on a conveyor belt of a tunnel boring machine. The speed of the conveyor flow 3 is in the range between 1 and 3 m/s, preferably in the range of 1.8 m/s to 2.5 m/s.

An impact body suspended on a traction cable 6, preferably in the form of a steel ball 5 here, plunges at least partially into the conveyor flow 3. A force transducer 7, which measures the force acting on the traction cable 6, is located on the suspension of the traction cable 6 on a mounting having a traverse 8. For typical excavated materials, which move at a speed between 1.8 m/s and 2.5 m/s in the conveyor channel 2, a steel ball of 6 cm diameter having a weight of approximately 900 g is preferably used.

The force transducer 7 is connected to an evaluation unit (not shown in Figure 1) for evaluating the sensor output signal, which samples the output signal of the force transducer 7 at a predetermined sampling frequency and outputs and/or temporarily stores the sampling values thus captured. In the experimental arrangement, the sampling frequency is, for example, 200 Hz, so that a force sampling value is captured and stored at intervals of 5 ms each.

Figure 2 shows in the upper diagram the measurement series captured in each case in an experimental arrangement, in which the sampling values were captured for a duration, for example, of approximately 60 seconds, wherein, for example, the sampling values captured in the first approximately 20 seconds, which were obtained during the startup of the experimental arrangement, were discarded.

The measurement series of the force measured values obtained at intervals of 5 ms each were divided into 61 measurement sequences of, for example, 128 sampling values each and therefore of approximately 0.64 seconds duration.

The lower diagram of Figure 2 shows by way of example a sensor signal profile during the time interval of 0.64 seconds, in which the 128 sampling values were obtained. The selection of 128 sampling values per sequences is also advantageous because a power of two facilitates the computer handling, for example in the case of a discrete Fourier transform for obtaining characteristic features from the measurement sequence.

Each of the 128 sampling values of a measurement sequence were input on the nodes of an input layer of a neural network after the neural network has been trained in a way described in more detail hereinafter. A correctly trained neural network then outputs a value corresponding to the input measurement sequence of 128 sampling values for a geotechnical parameter, in the preferred exemplary embodiment a value for the slump ("slump value"). In alternative embodiments, other and multiple geotechnical parameter values can also be output.

For a training, i.e. supervised teaching of the neural network, it is necessary to provide training data, which comprise pairs each made up of a measurement sequence of 128 force values and an associated value of the measured geotechnical parameter, i.e. in the present case the slump.

In one preferred embodiment, the following procedure was used for generating the training data for the neural network. Initially, samples of excavated materials of different compositions and consistencies were provided, here, for example, 13 samples which were characterized by an array of different slumps in the relevant range.

The geotechnical parameter, in the present case, for example, the slump, was captured metrologically for each of the samples. The samples were successively brought into an experimental arrangement in which a conveyor flow of the respective introduced sample was brought to a predetermined conveyor speed of 1.8 m/s or 2.5 m/s.

An impact body in the form of a steel ball fastened on a traction cable was introduced into the conveyor flow and after the settling of the arrangement at the predetermined speed, a measurement series of force sampling values was captured and stored, as shown by way of example in the upper image of Figure 2.

Measurement series of the described type were generated for each of the 13 samples, for example, preferably three measurement series here. Each of the three measurement series was in turn divided into 61 measurement sequences of 128 sampling values each, so that for each of the 13 sample excavated materials, 183 measurement sequences, thus a total of $13 \times 183 = 2379$ measurement sequences were generated and stored. The measured geotechnical parameter, the slump, of a sample was stored in assignment to the measurement sequence captured for this sample. Therefore, 2379 pairs of measurement sequences having 128 force values and an associated slump value were stored.

From the total number of 2379 measurement sequence-slump pairs, approximately 2000 pairs were randomly selected as training pairs for training the neural network. A residual amount of approximately 300 randomly selected pairs are used as validation data sets for checking the quality and suitability of the trained neural network.

The neural network was trained in that the square error and the gradient descent method were used as a loss function.

The weights of the neural network were initially preset to an arbitrary small value. The 128 sampling values which reflect the measured force profile within a time interval of 0.64 seconds were then input into an input layer of the neural network and, on the basis of the preset weights, an output value was obtained at an output layer, which is to correspond to the geotechnical parameter. The difference between the geotechnical parameter determined by the neural network and the actual value of the geotechnical parameter measured for the sample was then determined. As a function of these differences between the parameter values output by the neural network and the measured actual values of the samples, the weights were adapted in a known manner, wherein this was repeated for all pairs made up of force sampling values of a measurement sequence and the geotechnical parameter (slump) measured for the associated sample. In this case, the training pairs were input in random order.

The details of the supervised teaching carried out using a loss function of the square error and the gradient descent method are known to a person skilled in the art in the field of neural networks and do not have to be described in detail here.

The structure of an exemplary neural network, which was also used in the experimental arrangement, will be described hereinafter. Figure 3 shows a schematic representation of the neural network, which is simulated by the calculations of the data processing device, in which a value for a geotechnical parameter (here a slump) is determined from a measurement sequence

of 128 force sampling values. This artificial neural network initially comprises the 128 nodes of an input layer shown in the uppermost line of Figure 3. The calculations shown underneath simulate a convolution layer.

In a convolution, a convolution window (also referred to as a filter, kernel, or convolution core) of a predetermined width of nine weight values here, which is shown shaded in Figure 3, is linked with the values of 9 input nodes, wherein in each case a weight value is multiplied by the value of a node and the nine products thus formed are summed (vector scalar product). The result is assessed using an activation function and stored in a storage space of a so-called feature map.

The convolution window is then moved further by one node of the input layer (to the right in Figure 3), so that the nine weight values of the convolution window are then linked with the values of nodes 2-10 of the input layer (in each case multiplied and the results summed).

In Figure 3, in the line under the input layer, a first convolution window of the width 9 is initially shown below the nodes 1-9 of the input layer, wherein the result of this scalar product is stored in the first field in the first line of the feature map shown under the convolution windows. This is shown by an arrow connecting the first convolution window to the result field.

On the right adjacent to the first convolution window, a first convolution window moved further by eleven steps is shown in a dashed representation, which is to illustrate that in this position the nine weights of the first convolution window are linked with the values of nodes 11-19 of the input layer, wherein the result is stored in the eleventh field of the first line of the feature map.

Finally, a further dashed representation of the first convolution window is shown on the very right, which is positioned so that its weight values are linked with nodes 120-128 of the input layer, wherein the result is stored in the 120th field of the first line of the feature map, which is again indicated by a corresponding arrow.

In the preferred exemplary embodiment shown in Figure 3, a total of 64 different convolution windows or filters are used in the first convolution layer, which is illustrated by the numbering 1, 2, and 64 on the left adjacent to the filter blocks. Accordingly, results are generated by the overall convolution operations, which are stored in a feature map having 120 fields in each of 64 lines. These operations simulate a first one-dimensional convolution layer of the neural network. The convolution layer is one-dimensional, wherein a one-dimensional convolution window is moved over a one-dimensional input layer.

Before their further processing, the values stored in the feature map are preferably also assessed using a so-called activation function. This assessment either already takes place during their calculation (scalar product) before storage in the feature map or thereafter for the entire calculated feature map. Both procedures are equivalent in a simulated neural network.

In the preferred exemplary embodiment shown here, a so-called reLU activation function is used, i.e. $\text{reLU}(x) = \text{Max}(0, x)$. This means that all negative values are replaced by zero, while the positive values remain unchanged.

To reduce the calculation time and the computing effort, the amount of data of 120×64 elements stored in the feature map is preferably reduced in a so-called pooling layer, in that a new element is obtained in each case from a predetermined number of elements of the feature map. In the preferred exemplary embodiment shown in Figure 3, an average value is formed from each 10 elements of a line of the feature map and this is temporarily stored (in a further node layer). This averaging of 10 elements in each case is represented by a curved bracket with an arrow by way of example for the first 10 elements of the 1st, 2nd, and 64th line.

A total of $12 \times 64 = 768$ average values result. Due to the averaging, this operation is also referred to as average pooling. A neural network would also be conceivable which uses so-called max pooling instead of average pooling in its pooling layer, in which only the maximum value is selected in each case from the predetermined number of starting values (also referred to as subsampling).

This pooling is followed by a further convolution layer, as shown in Figure 3. Upon the further convolution, 64 different convolution windows each having a width of 9 are again moved in succession over the lines of the results of the pooling of 12 elements each, wherein upon each movement of a convolution window of width 9 over a line of 12 elements, four result elements are formed. In this case, the 64 different convolution windows or filters are moved in succession (or also in parallel) over a line of 12 elements, wherein the first, the second, the third, and the fourth result elements of the 64 filters are each summed.

This is repeated for each of the 64 lines of the results of the pooling, so that overall a matrix of 4×64 elements is formed, as shown in Figure 3. The results of these convolution operations are also assessed using an activation function, preferably again a reLU activation function. The 4×64 assessed convolution results are then resorted in a so-called flattening into a vector of 256 elements, wherein this vector is shown in Figure 3 as a node layer of 256 nodes.

Three further layers of nodes of the neural network follow, which have 64, 32, and 16 nodes, respectively. These four concealed node layers ("hidden layers") having 256, 64, 32, and 16 nodes, respectively, which are shown at the bottom in Figure 3, are completely linked layers ("fully connected layer"), i.e. each node is linked with each node of the following layer, wherein these linkages are not completely shown in Figure 3.

A weight is assigned to each linkage between two nodes. Each of the nodes shown in Figure 3 additionally in turn implements an activation function, preferably the reLU activation function. An output layer follows the last layer having 16 nodes, which in the example shown in Figure 3 only comprises one output node for outputting a value, for example for the slump here. No activation function is assigned to this node.

In the course of the supervised teaching, starting values are to be assigned both to the nine weights of each of the 64 convolution windows of the first convolution layer and also the nine weights of each of the 64 windows of the second convolution layer and the $256 \times 64 + 64 \times 32 + 32 \times 16 + 16 = 18,960$ weights of the completely linked layers, and the weights of additionally present bias neurons, and then these values are to be adapted by a suitable method.

Of course, many alternative configurations are conceivable for suitable neural networks. For example, instead of 64 filters of the convolution layers, only 16 layers could also be used and at the same time the pooling could be omitted after the first convolution layer. In the network configuration, it is always to be balanced that the number of the teachable parameters (weights) is not excessively low in order to achieve good prediction results, but should also not be excessively high, because then overfitting of the neural network can occur. The structure of a neural network described here on the basis of Figure 3 is the result of a large number of trials using different neural networks.

Claims

1. A method for determining at least one geotechnical parameter of an excavated material of a tunnel boring machine, wherein
the excavated material is deposited on a conveyor device (2) for transporting the excavated material, an impact body (5) is arranged in a conveyor flow (3) of the excavated material such that it plunges at least partially into the excavated material, wherein the excavated material in the conveyor flow (3) has a flow speed which is either predetermined or is measured,
a measured variable which corresponds to a force exerted by the excavated material of the conveyor flow (3) on the impact body (5) is measured, wherein a time sequence of measured values of the measured variable is captured, and
the at least one geotechnical parameter is determined from a section of the sequence of measured values in that the section of the time sequence of measured values is input into a data processing device and is processed thereby such that at least one output value corresponding to the at least one geotechnical parameter is output, wherein either the processing of the measured values is based on the predetermined flow speed or a value for the measured flow speed is input and taken into consideration in the processing of the measured values.
2. The method for determining at least one geotechnical parameter as claimed in claim 1, characterized in that the impact body is arranged in an open conveyor flow of the excavated material.
3. The method for determining at least one geotechnical parameter as claimed in claim 1 or 2, characterized in that a predetermined flow speed of the conveyor flow is set and is kept constant during the capture of the time sequence of measured values of the measured variable.
4. The method for determining at least one geotechnical parameter as claimed in any one of claims 1 – 3, characterized in that the time sequence of measured values is captured at a constant sampling frequency.
5. The method for determining at least one geotechnical parameter as claimed in any one of claims 1 – 4, characterized in that the section of the time sequence of measured values corresponds to a measurement duration of 0.25 s to 60 s, preferably of 0.5 s to 1 s.
6. The method for determining at least one geotechnical parameter as claimed in any one of claims 1 – 5, characterized in that the data processing device implements a trained neural network which has multiple layers of nodes, wherein all linkages between the nodes are assigned weights and

predetermined activation functions are assigned to the nodes, wherein the weights have been set beforehand by means of a training method,

wherein a matrix of input data is obtained from the section of the sequence of measured values and the matrix of input data is input into an input layer of nodes of the neural network, and

wherein the at least one output value corresponding to the at least one geotechnical parameter is output by at least one node of an output layer of the neural network.

7. The method for determining at least one geotechnical parameter as claimed in claim 6, characterized in that a predetermined number of characteristic features is calculated from the section of the time sequence of measured values and these features are used as the matrix of the input data.

8. The method for determining at least one geotechnical parameter as claimed in claim 6, characterized in that the section of the time sequence of measured values is used in scaled form as a one-dimensional matrix of the input data.

9. The method for determining at least one geotechnical parameter as claimed in any one of claims 6 – 8, characterized in that a neural network is simulated in a program-controlled manner by the data processing device, or that a feedforward neural network having a convolutional neural network is simulated by the data processing device, or that a convolutional neural network having a first convolution layer having a following pooling layer and a following second convolution layer having multiple following completely linked layers is simulated by the data processing device.

10. The method for determining at least one geotechnical parameter as claimed in any one of claims 6 – 9, characterized in that before the input of the section of the time sequence of measured values to determine the at least one geotechnical parameter, the weights are set in the training method in that

a) for a predetermined selection of a plurality of excavated material samples of different compositions having different geotechnical parameters, in each case:

a1) the at least one geotechnical parameter of the excavated material sample is measured or determined and stored as a target parameter value,

a2) the impact body is arranged in a conveyor flow of the excavated material sample such that it plunges at least partially into the excavated material, wherein the excavated material in the conveyor flow has a predetermined flow speed, and a measured variable which corresponds to a force exerted by the excavated material of the conveyor flow of the excavated material sample on the impact body is measured, wherein a time sequence of measured values of the measured variable is captured,

a3) pairs each made up of a section of the sequence of measured values are stored in assignment to the target parameter value,

b) starting values are assigned to the weights in the neural network implemented by the data processing device,

c) for a pair made up of a section of the sequence of measured values and assigned target parameter value:

c1) the at least one geotechnical parameter is determined from the section of the sequence of measured values in that the section of the time sequence of measured values is processed by the data processing device implementing the neural network such that at least one output value corresponding to the at least one geotechnical parameter is output,

c2) the difference between the output value and the assigned target parameter value is then determined, and

c3) the weights are changed depending on the difference,

wherein steps c1) to c3) are repeated for a next pair made up of a section of the sequence of measured values and assigned target parameter value, wherein the selection of the pairs takes place in random order,

wherein steps c1) to c3) are executed for a predetermined proportion of the pairs stored in step a), which is used as the training set.

11. The method for determining at least one geotechnical parameter as claimed in any one of claims 1 – 10, characterized in that a slump of the excavated material is determined as the geotechnical parameter.

12. A method for setting the consistency of a conditioned excavated material of an earth pressure balance shield tunnel boring machine, wherein a conditioning agent is admixed with the excavated material for its conditioning in the excavation chamber,

the conditioned excavated material is conveyed using conveyor devices out of the excavation chamber, wherein at least one geotechnical parameter, preferably a slump, is determined in an automated manner according to a method as claimed in any one of claims 1 – 11 in an open conveyor flow formed on one of the conveyor devices, and

the amount of the conditioning agent to be admixed is regulated as a function of the geotechnical parameter thus determined.

13. A method for classifying an excavated material of a tunnel boring machine, wherein the conditioned excavated material is conveyed out of the excavation chamber using at least one conveyor device, wherein at least one geotechnical parameter, preferably a slump, is determined in an automated manner according to a method as claimed in any one of claims 1 – 11 in an open

conveyor flow formed on one of the conveyor devices, and the excavated material is classified as a function of the determined geotechnical parameter.

14. A device for determining at least one geotechnical parameter of an excavated material arising in a tunnel boring machine, in particular for application of a method as claimed in any one of claims 1 to 11, comprising:

a conveyor device for transporting the excavated material such that a conveyor flow (3) of the excavated material having a flow speed is formed in an open conveyor channel (2), wherein the conveyor device has a unit for setting a predetermined flow speed and/or a unit for measuring the flow speed,

an impact body (5) arranged in the open conveyor channel (2), which plunges at least partially into the conveyor flow (3) of the excavated material,

a measuring device (7), connected to the impact body (5), for measuring a measured variable, which corresponds to a force exerted by the excavated material of the conveyor flow (3) on the impact body (5),

a device coupled with the measuring device (7) for capturing sampling values of the measured variable, for converting the sampling values of the measured variable into digital measured values, and for outputting a time sequence of digital measured values,

a storage device for temporarily storing the sequence of digital measured values, and

a data processing device coupled with the storage device, which is configured so that it processes a section of the sequence of digital measured values and outputs at least one output value corresponding to the at least one geotechnical parameter.

15. The device for determining at least one geotechnical parameter as claimed in claim 14, characterized in that the data processing device is configured so that it generates and processes a matrix of input data from the section of the sequence of digital measured values and outputs at least one output value corresponding to the at least one geotechnical parameter and, in the processing, takes into consideration either the set predetermined flow speed or a measured value of the flow speed,

wherein the data processing device implements a trained neural network which has multiple layers of nodes, wherein all linkages between the nodes are assigned weights and the nodes are assigned predetermined activation functions, wherein the weights have been set beforehand by means of a training method,

wherein the matrix of input data is input into an input layer of nodes of the neural network and the at least one output value corresponding to the at least one geotechnical parameter is output at at least one node of an output layer of the neural network.

16. The device for determining at least one geotechnical parameter as claimed in claim 14 or 15, characterized in that the impact body (5) is formed as a ball, preferably as a steel ball having a weight of 500 g to 2000 g, preferably 800 g to 1000 g.

17. The device for determining at least one geotechnical parameter as claimed in claim 16, characterized in that the ball (5) is fastened on a pivotably suspended rod or a traction cable (6) and a sensor (7) for capturing the measured variable is coupled with the rod or the traction cable (6), wherein the measured variable corresponds to a traction force absorbed by the rod or the traction cable (6).

18. The device for determining at least one geotechnical parameter as claimed in claim 15, characterized in that the data processing device is configured so that it simulates a feedforward neural network having a one-dimensional convolutional neural network, wherein preferably the data processing device is configured so that it simulates a convolutional neural network having a first convolution layer having a following pooling layer and a following second convolution layer having multiple following completely linked layers.