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RAFAŁ PIERSZALIK[1*]

# SIGNIFICANCE OF A NEW PRELIMINARY TREATMENT METHOD OF THE PEN206_18 BOREHOLE PENETROMETER'S PRESSURE READOUTS FOR A RELIABLE ANALYSIS OF ROCK STRESS-STRAIN PARAMETERS

This article describes some selected aspects of a preliminary treatment of measurement cycle results obtained by a new Pen206_18 type hydraulic borehole penetrometer (a borehole jack type), a tool of an *in situ* determining of mechanical properties of rocks. The pre-treatment of the measurement cycle results is a necessary step to prepare the data for a following appropriate analysis of stress-strain parameters of rocks. Aforementioned aspects are focused mainly on a pre-treatment of hydraulic pressure readouts.

The Pen206_18 type penetrometer is a modified version of a standard Pen206 type penetrometer. The standard version, based on a digital measurement of a critical hydraulic pressure, has been in use in polish hard coal mines for almost 15 years to determine various rock strength parameters. In contrary, the Pen206_18 type penetrometer now provides simultaneous recording of two main measurement cycle parameters (hydraulic pressure and a head pin stroke) during the whole measurement cycle duration. A recent modification of the penetrometer has given an opportunity to look closer at various factors having an influence on the measurement cycle data readouts and, as a consequence, to lay a foundation for a development a new penetrometric method of determining stress-strain parameters of rocks.

In this article it was shown that just before a main stage of the measurement cycle, a transitional stage could occur. It complicates a determination of the beginning of an useful set of measurement cycle data. This problem is widely known also in other static *in situ* methods of determining stress-strain parameters. Unfortunately, none of various known workouts of this problem were sufficiently adequate to the pre-treatment of the penetrometric measurement cycle results. Hence, a new method of determining the beginning of the useful set of pressure readouts has been developed. The proposed method takes into account an influence of an operational characteristics of the measuring device. This method is an essential part of a new pre-treatment procedure of the Pen206_18 measurement cycle's pressure readouts.

**Keywords:** rock; stress; strain; analysis; penetrometer; jack

[1] CENTRAL MINING INSTITUTE (GIG), 1 GWARKÓW SQ., 40-166 KATOWICE, POLAND

* Corresponding author: rpierszalik@gig.eu

# 1. Introduction

This article presents some selected aspects of a preliminary processing (a pre-treatment) of measurements results obtained by a new Pen206_18 type hydraulic borehole penetrometer, i.e. a borehole jack, by [1]. It is a tool designed to determine a deformational characteristics of rock in a drilled borehole. This tool's principle of use is similar to a Goodman Jack [2,3] but the main difference is that rock mass is loaded not by two identical opposite loading platens but mainly by a 5 mm-diameter pin. A recently updated penetrometric method required a development of an appropriate pre-treatment of the measurement readouts. The pre-treatment issues of the Pen206_18 type penetrometer measurements presented in this article are examples of typical potential measurement problems related also with other similar static-type methods of determining stress-strain properties of rocks.

The pre-treatment process is used to prepare a measurement cycle data set of measurement parameters (specific for a given static method type) for an analysis of rock stress-strain parameters. The pre-treatment is about getting rid of an influence of a measuring device properties and measurement conditions from the results data set. It includes an extraction of the set of useful results from an entire measurement cycle data set as well as applying adjustments resulting from an impact of mechanical properties [4] and an operational characteristics of the measuring device. Due to a nature of performing *in situ* measurements and both a hardware and software design of the Pen206_18 type penetrometer, the pre-treatment can be performed only using an analytical computer software after the end of a whole measurement cycles session. However, this is a minor inconvenience in comparison to a main advantage of the new penetrometer type – to be able to determine *in situ* stress-strain parameters of rock mass, especially for strata having too low cohesion for obtaining rock samples for laboratory testing method. And knowledge about the deformational parameters of rock mass is often needed for example to create valid numerical models of the rock mass [5] or perform various tasks related with a stability of underground openings [6].

Some of the pre-treatment aspects of the Pen206 type penetrometer haven't been available to be resolved until the recent development of the Pen206_18 type (Fig. 1) borehole penetrometer. This type is a heavy-modified version of a Pen206 type penetrometer [7,8] which in turn has been in use for 15 years in polish hard coal mines as a main *in situ* device to determine specific rock stress-strain parameters, namely a compressive and tensional rock strength. The new Pen206_18 type penetrometer (Fig. 1) has been developed mainly to provide a data for a rock stress-strain behaviour analysis. A detailed description on the principle of use of the penetrometric method a reader can find in for example [9,4].

One of the main aspects, i.e. an influence of mechanical properties of the penetrometer head's measurement assembly on a real pin stroke (that could be represented as a so-called stiffness of the head's assembly), has been discussed already [4]. Another main aspect, i.e. the influence of an operational characteristics on pressure readouts is showed in this article. Influences of the aforementioned aspects on the measurement results are significant and therefore they should be eliminated or as limited as possible, e.g. by applying appropriate adjustment to the measurement results.

In order to apply these adjustments, first an useful data set should be extracted from the measurement cycle data set. However, it is often very difficult to properly determine the beginning of this set. It is due to a fact, that usually it is very hard to properly set the measuring device for the measurement cycle (i.e. to set and stabilise a penetrometer's head inside the borehole).

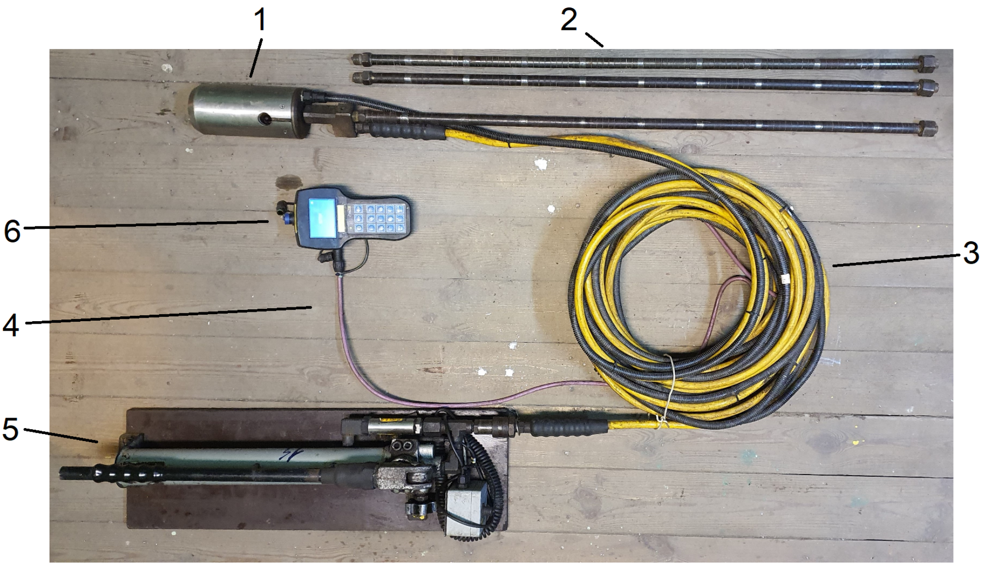


Fig. 1. An assembled Pen206_ type hydraulic penetrometer set: 1 – a head with a pin, 2 – spare pushing rods, 3 – an electric signal cable, 4 – a hydraulic hose, 5 – a hydraulic pump, 6 – a control and recording panel

This could cause a significant distortion on the initial part of the measurement cycle readouts, until the aforementioned head is fully set against the borehole wall.

Unfortunately, there is not much information in a scientific literature on issues related with the determination of the beginning of the useful data set. More, known generic workouts of this problem were not sufficiently adequate to adapt to the pre-treatment of the penetrometric measurement results. Hence, as a part of the pre-treatment procedure, a new method of the determination of the beginning of the useful data set was proposed. It is an essential part of a new way of interpreting measurement cycle results obtained by the Pen206_18 type penetrometer.

## 2. Main issues of the pre-treatment of the *in situ* measurement cycle results

Among issues of the pre-treatment of the measurement cycle results of various static-type methods of determining stress-strain properties of rocks, a most problematic seems to be a correct determination of a beginning of the useful results data set. In other words, knowledge of the parameters of the beginning of the useful results set allows for an appropriate use of various adjustments for measured parameters values.

The issue of determining the beginning of the set of useful results applies to virtually every static method of determining the stress-strain parameters of rocks (including strength parameters), particularly to field (*in situ*) methods. This beginning could be described by parameters of a so-called appropriate preparation of the measuring device for the measurement cycle.

## 2.1. The issue of the appropriate preparation of the measuring device for an *in situ* measurement cycle

In order to obtain the state of the appropriate preparation of the device for the measurement cycle, a first step is to set and stabilise the measuring device in relation to the tested rock, so that it does not undergo undesirable movement while exerting increasing pressure on the rock during the main stage of the measurement cycle. In a second step, the working element of the device should be brought just into a contact with the rock surface, but without applying any force (pressure) on it yet.

However, under real-life measurement conditions, the appropriate preparation of the device for measurement usually is technically and organisationally complicated, generally due to a weight and dimensions of the device (Fig. 2) [10,11] or an inability to stabilise the device and adjust it to the surface of the tested rock, like for example inside a drilled borehole. Some methods, discussed in, for example [2] as well as the borehole penetrometric method [1], do not at all provide any means of preparing the working element of the device for the measurement cycle.

Fig. 2. Preparation of the measurement stand of the PJT method (after: [11])

## 2.2. Known workarounds of the determination of the parameters of the beginning of the set of useful results

There are two popular generic approaches to limit the influence of inappropriately prepared measurement device on a determination of the beginning of the useful results set.

A first approach is to initially set the device with some preliminary force exerted on the rock together with an external stabilisation of the device. Then, a value of the setting force of the stabilised device should be decreased so to be able to reduce the effective pressure of the working element on the rock surface to zero. In practice, however, this is very difficult to obtain, as the minimum value of the setting force is specific to each possible position of the device and it cannot be determined without creating a risk of destabilizing the initially set device for the measurement cycle. Unfortunately, the determination of the beginning of the set of results on the basis of rock unloading may be difficult also due to the phenomenon of elastic hysteresis, e.g. [11].

Hence, a second approach is based on exerting a relatively low value of the setting force on the rock surface just to ensure the state of appropriate preparation of the device is obtained. Then, measurement cycle results above a so-called threshold value of the force (or pressure or another measured corresponding unit) are taken into account for a further analysis. For a such threshold value, it is assumed that the rock deformation is none. The threshold value and its corresponding extension of the working element are then considered the parameters of the appropriate preparation of the device for the measurement cycle. However, a disadvantage of a such method is the risk of a loss of some unknown portion of the useful results set and, consequently, underestimation of the maximum stress and corresponding rock deformation values.

Another kind of a solving the problem of a lack of rock stress-strain properties knowledge is to use some indirect estimates of deformational properties [12].

Unfortunately, little information is available in the scientific literature on how to extract the set of useful results from the standard penetrometric measurements. Instead, only some ready-to-use coefficients are provided [1,13], however without a detailed explanation on how the value coefficients were obtained. In fact, the coefficients are related only with a single critical pressure value. Therefore, an analysis of a nature of the transitional stage of the penetrometric measurement cycle has been performed.

## 2.3. Analysis of a nature of the transitional stage of the penetrometric measurement cycle

Due to the nature of the penetrometric test method it is virtually impossible to ensure the appropriate setting of the penetrometer's head within the borehole before beginning of the measurement cycle. As a consequence, a transitional stage occurs. It is a stage of setting the penetrometer's head within the borehole, using the head's pin. Figs. 3 and 4a÷4c show an example of the problem of the transitional stage, during measurement cycle preformed in a horizontally drilled borehole.

Fig. 3. A photo of the penetrometer head positioned within the horizontal borehole with the pin oriented horizontally

According to the methodology of penetrometric measurements [1], the head should be oriented so that the pin can extend in the direction parallel to the rock bedding plane line (in this case horizontally) (Figs. 3 and 4a). Then, the pin moves freely (a so-called unstrained pin stroke) out of the head until reaching an initial contact with the borehole wall surface.

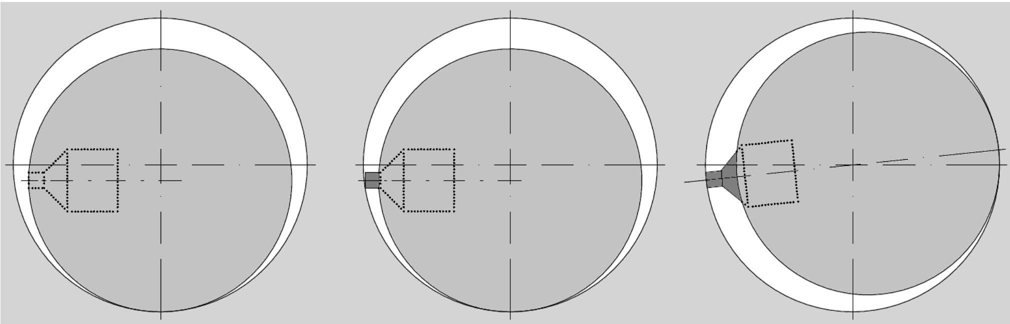


Fig. 4. Characteristic states of the initial and transitional stages of the penetrometer head located in a horizontal or inclined borehole: a) the pin in the initial position within the head, ready to extend, b) an initial contact of the pin with the borehole wall, c) a full contact of the pin assembly with the borehole wall

Fig. 4b shows a first characteristic state of a process of the setting of the head within the borehole, i.e. the moment of initial contact of the pin with the rock (Fig. 4b). However, due to a difference of diameters of the borehole and the head, and due to a gravity influencing a position of the head within the borehole, while continuing of extending the pin, the head will slip on the side surface of the hole, trying to set itself in the borehole until the moment of achieving complete setting of the head (Fig. 4c). Another consequence of the head setting is, the head may rotate by a few degrees from its initial orientation. This phenomenon may be noticeable especially in inclined or horizontal boreholes when extending the pin in a direction close to the horizontal, where gravity has a significant impact on the initial position of the head in the borehole (Figs. 4a÷4c).

In other words, to set the head within the borehole, a some value of the force exerted by the pin is needed. This force is exerted by the pressure of the hydraulic medium within the head body thru the piston assembly. However, some part of the force is needed to overcome the friction forces between the head edge and the rock surface.

In a consequence, a necessary condition of the state of the appropriate preparation of the device for the measurement cycle, i.e. no exerting pressure on the rock surface, cannot be ever fulfilled. This due to a fact, that hydraulic pressure of the state of the full pin contact cannot be lowered without the risk of another unwanted head slippage.

Therefore, it is needed to determine parameters of a theoretical appropriate preparation of the device for the measurement cycle (a so-called proper pin contact with the borehole wall) empirically. It is a very important conclusion of the mentioned analysis.

Bearing the mentioned conclusion in mind, a new method of determination of parameters of the appropriate setting of the penetrometer's head has been proposed. It is explained on an example of *in-situ* results of measurements done with the hydraulic Pen206_18 borehole penetrometer.

An explanation of this method needs first to define its prerequisities and specific measurement cycle parameters, which this method is based on.

### 2.4. Description of the penetrometric measurement cycle's parameters

Assuming that the examined borehole section's wall has a cylindrical shape and the rock mass isn't cracked in any way, a simplified set of the penetrometric test results (i.e. pressure in the hydraulic system $p_{meas}$ and the pin stroke $l_{meas}$), usually take a general shape of a one of two charts shown in a Fig. 5. A chart in a Fig. 5a is an example of an idealistic results set. Such a set could be obtained as an effect of the appropriate setting of the head for measurement. In contrary, a Fig. 5b shows a typical, real-life chart of the results of the measurement cycle when it was not possible to properly prepare the penetrometer head for measurement. It should be noted that, in simple term, points P0, P1, P2 and P3 are related with an idealistic operational characteristics of the penetrometer's head (that is, being an unstrained pin stroke characteristics without an influence of friction forces between head parts).

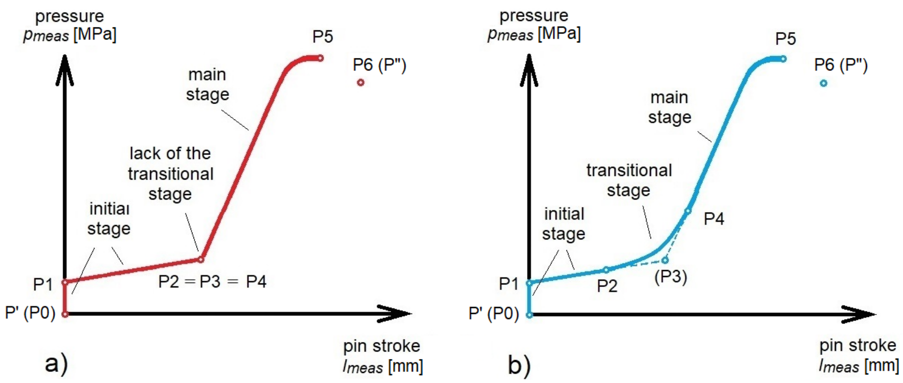


Fig. 5. Two examples of the Pen206_18 penetrometer measurement cycle results:
a) the ideal measurement cycle characteristics – points P' (P0), P1, P3, P5 and P6 (P");
b) the real-life measurement cycle characteristics – points P' (P0), P1, P2, P4, P5 and P6 (P")

The real-life penetrometric measurement cycle results belong to three main stages, divided into phases F0÷F6, separated by a few characteristic states marked by border points P' (P0), P1, P2, P4, P5 and P6 (P") (Fig. 5b). Each point $P_n$ described above is characterised by two parameters, the pin stroke $l_{Pn}$ and the pressure $p_{Pn}$ in a following form:

$$P_n = [l_{Pn}; p_{Pn}] \tag{1}$$

**I.** An initial stage (Fig. 5, from the point P0 to P2) – the unstrained pin stroke:
- point P' – a data recording start point,
- phase F0 – a phase of waiting for the beginning of increasing the pressure in the hydraulic system – this phase is characterised by pin stroke $l_{meas}$ = 0 mm and pressure $p_{meas}$ = 0 MPa,

– point P0 – a starting point of increasing the pressure in the hydraulic system,
– phase F1 – the phase of increasing pressure in the hydraulic system but with no pin stroke yet,
– point P1 – a starting point of the piston stroke,
– phase F2 – the unstrained stroke of the piston assembly (until reaching the initial contact of the pin with the borehole wall).

**Ia.** A transitional stage (Fig. 5, from the point P2 to P4) – setting of the head in the borehole:
– point P2 – point of initial contact of the pin with the surface of the borehole.
– phase F3 – the phase of setting the head-pin assembly in the hole, as a result of clearing the gaps between the head and the surface of the borehole wall, shown in Fig. 5b – this phase is represented by the characteristics between points P2 and P4,
– point P3 is the point of proper contact of the pin (i.e. the pin-head system) with the borehole wall. This point indicates the parameters for the appropriate setting of the penetrometer head for measurement. In the Fig. 3, it can be seen that this point isn't located on the characteristics of the test results, as it cannot be determined directly from the measurement results.

**II.** A main stage (Fig. 5, from the point P4 to P5) – increasing pressure on the rock surface by the pin:
– point P4 – is the point of so-called full contact of the pin with the borehole wall. This is the point from which it is assumed that the measurement characteristics is not disturbed anymore by the head setting within the borehole,
– phase F4 – the phase of increasing pressure of the pin system, in order to try to cause the destruction of the rock structure – it starts at point P4,
– point P5 – is a critical point of the penetration cycle, characterising the achievement of a critical pressure, resulting in a dynamic destruction of the rock structure during the critical stage.

**IIa.** A critical stage (Fig. 5, between points P5 and P6) – a dynamic destruction of the rock structure:
– phase F5 – the phase of dynamic destruction of the rock structure, the effect of which is a post-destruction crater with a pin indented in it. This stage lasts so short that it is not possible to register the course of pressure changes and its stroke with its measuring system, hence an empty space between P5 and P6 points.
– point P6 – is a post-critical point of the penetration cycle, describing the parameters of the pin indentation in the post-failure crater.

**IIb.** A post-critical stage (optional – not present on Fig. 5):
It should be noted that even if a critical point of the penetration cycle P5 has been already achieved, the subsequent phases F4 and F5 may occur again as a result of continuation of increase of the hydraulic pressure. Consequently, new critical points may occur again.

**III.** The final stage (optional – not present on Fig. 5): unloading of the hydraulic pressure and a return of the pin to its initial position within the head:
– phase F6 – a phase of pressure discharge in the hydraulic system of the head in order to withdraw the pin to the head,
– data recording end point P”. On Fig. 5 it is the same as the point P6.

This point may be located also in the earlier phases of the measurement cycle, regardless of whether the rock structure has been damaged, the pin has been fully extended, the maximum pressure in the hydraulic system has been reached.

# 3. Selected aspects of the pre-treatment procedure of the Pen206_18 penetrometer measurement cycle results

A typical penetrometric session consists of a few hundred measurement cycles, so a manual pre-treatment of the results would be heavily time-consuming. Therefore, it was necessary to develop a pre-treatment procedure of the results that could be implemented within a computer analytical software.

The pre-treatment procedure of the results of the penetrometric measurement cycle consists of six main subsequent stages:

1. Obtaining a correction characteristics of the penetrometer's pin stroke readoutsand the operational characteristics of the penetrometer,
2. Verification of the suitability of measurement data for the next pre-treatment stages, based on the operational characteristics of the penetrometer,
3. Determination of the parameters of the appropriate setting of the penetrometer's head,
4. Application of adjustments on the measurement data values, resulting from the penetrometer's head mechanical deformability and its operational characteristics,
5. Application of other possible adjustments resulting from, for example, the conditions of the measurement cycle,
6. Conversion of the pin stroke values into rock strain values.

Due to the extensive subject of the pre-treatment of the results of penetrometric measurement cycle, in the article of [4] a one of the fundamental pre-treatment aspects has been described already, that is an impact of mechanical deformability of the penetrometer head's assembly on the pin stroke measurement results. This aspect belongs to the stage 1 of the pre-treatment procedure.

This article, however, focuses mainly on the pre-treatment's stages 2 and 3, especially on the new method of determining the parameters of the appropriate setting of the penetrometer's head for the measurement cycle. The determination of the parameters of the appropriate setting of the head is inseparably connected with the verification stage, therefore both stages of the pre-treatment need to be described in this article. The stage 3's method could be used only after a successful verification of the suitability of measurement data (stage 2). Additionally, in section 3.2. a practical use of the aforementioned method has been presented to calculate an effective pressure acting by the pin on the borehole wall surface.

The determination of parameters of the appropriate setting of the penetrometer's head is one of key aspects of the penetrometric measurement data pre-treatment. These parameters are necessary for the appropriate application of the pin stroke and pressure adjustments (stage 4). Main issues related with the appropriate preparation of the penetrometer for the measurement cycle are already discussed in section 2 of this article.

## 3.1. Verification of the suitability of the measurement data for the pre-treatment adjustments of the hydraulic pressure readouts

The pressure measurement cycle data set first should be verified if it is suitable for the further pre-treatment stages. The goal of this verification is to check if the recorded data set, starting with the parameters of the data recording start point P' and ending with the parameters of the a data ending point P", covers a complete transitional stage. Only then parameters of the proper pin contact point could be determined an, in consequence, the hydraulic pressure readouts adjustment.

For better understanding of this verification process (the pre-treatment's stage 3), first a data set of the operational characteristics of the penetrometer should be obtained and processed during the stage 1 of the pre-treatment procedure. This operational characteristics of the penetrometer is represented by a dependency between an unstrained pin stroke and a hydraulic pressure (Fig. 6).

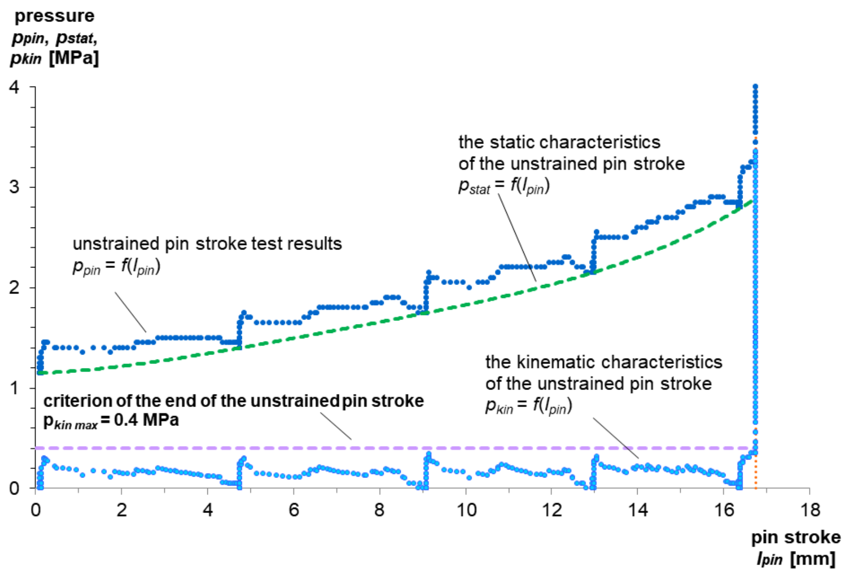


Fig. 6. Chart of the unstrained pin stroke characteristics analysis with a determinedthe static characteristics of the unstrained pin stroke $p_{stat} = f(l_{pin})$, the kinematic characteristics of the unstrained pin stroke $p_{kin} = f(l_{pin})$ and the pressure of the criterion of the end of the unstrained stroke $p_{kin\,\max}$

The unstrained pin stroke characteristics $p_{pin} = f(l_{pin})$ is a sum of two characteristics:

1. A static characteristics of the unstrained pin stroke $p_{stat} = f(l_{pin})$ describes a pressure needed to obtain a certain, stable position of the pin,
2. A kinematic characteristics of the unstrained pin stroke $p_{kin} = f(l_{pin})$ is related with friction force coefficients related with pin kinematics (pin's velocity and acceleration).

The static characteristics of the unstrained pin stroke is determined by a polynomial regression of a few points of stable positions of the pin, obtained between each hydraulic pump pressure increase cycle. However, the kinematic characteristics of the unstrained pin stroke is determined on a basis of the values of the unstrained pin stroke test results, subtracted with corresponding values of the static characteristics of the unstrained pin stroke. A main reason of determining the kinetic characteristics is to find a maximum possible pressure increase needed to begin and maintain a quasi-static movement of the pin, as it happens during the main stage (i.e. phase F4) of the penetrometric measurement cycle. Both types of the unstrained pin stroke characteristics should be obtained from the unstrained pin stroke measurement cycle results set, if there are at least four points of stable, unstrained pin positions The pressure data verification is carried out by comparing the measurement cycle results set $p_{meas} = f(l_{meas})$ (Fig. 7) with two empirical characteristics determined from the unstrained pin stroke characteristics, $p_{pin} = f(l_{pin})$ (Fig. 6).

An initial, visual inspection of the chart (Fig. 7) suggests an occurrence of initial, main and critical stages of the measurement cycle (i.e.the phase of the unstrained pin stroke F2 and the main phase of the measurement cycle F4). It can also be observed that a transition between these main phases is gradual (to a some degree) which indicates an existence of the transitional phase F3.

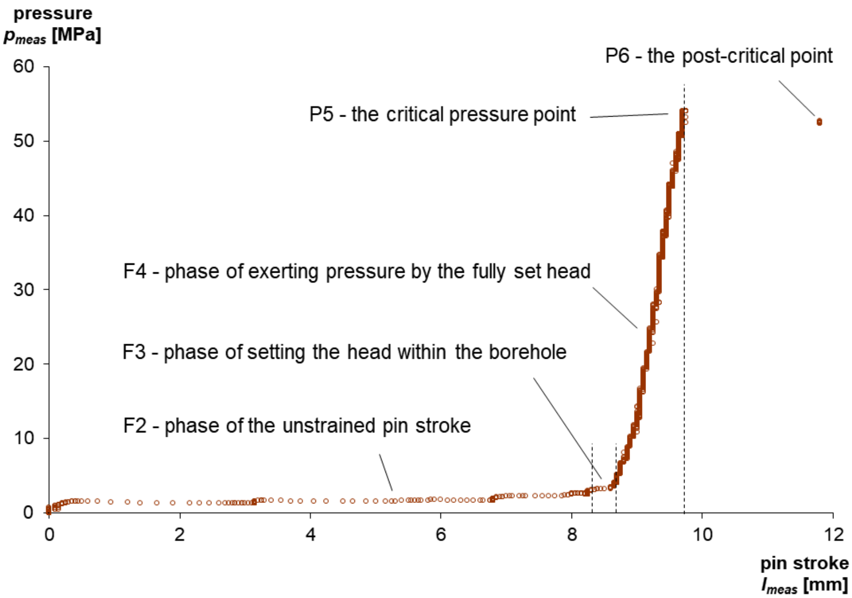


Fig. 7. An example of the Pen206_18 penetrometer *in situ* measurement cycle results, with the preliminary description of the main phases and border points of the measurement cycle

The data verification stage consists of three steps:

1. Checking if the recording process has been started before achieving a contact of the pin with the borehole wall. The necessary condition for the positive passing of this step is to check if the first recorded pressure value $p_{P'}$, for a given first recorded pin stroke value $l_{P'}$ from the measurement cycle data set $p_{meas} = f(l_{meas})$ is not higher than the sum of pressure value derived from the static pin stroke characteristic $p_{stat} = f(l_{pin})$ for the pin stroke $l_{pin}$ equal to $l_{P'}$ and a pressure of the criterion of an end of an unstrained pin stroke, i. e. a maximum determined pressure value of the kinematic pin stroke characteristics $p_{kin\,\max}$:

$$p_{P'}(l_{P'}) \le p_{stat}(l_{pin}) + p_{kin\,\max}, \text{ for } l_{pin} = l_{P'} \tag{2}$$

2. Checking if the initial contact of the pin with the borehole wall has been achieved. A main purpose of this step is to cut off the initial part of the recorded data set from a next step of the data verification process. For this verification step's assessment, a determination of the parameters of the initial pin contact point P2 is required. This point's determination is described in detail in a 3.1.1. section. The sufficient condition of achieving this state is

to determine if the pin stroke value of the initial pin contact point P2 ($l_{\mathrm{P2}}$) is lower than the maximum recorded pin stroke $l_{meas\,\max}$:

$$l_{\mathrm{P2}} < l_{pin\,\max} \tag{3}$$

If this condition is not met, it means that the pin has achieved its maximum stroke without achieving the contact with the borehole surface.

3. Checking if the full contact of the pin with the borehole wall has been achieved (before reaching a pin's maximum stroke). A sufficient condition of achieving this state is to determine if the pin stroke value of the full pin contact point P4 ($l_{\mathrm{P4}}$) is lower than the maximum recorded pin stroke $l_{meas\,\max}$. This step of the verification process is carried out on the set of the measurement data starting from the parameters of the initial pin contact point P2.

$$l_{\mathrm{P4}} < l_{pin\,\max} \tag{4}$$

Positive assessment of all three steps of the data verification is necessary to determine the parameters of the appropriate preparation of the device for the measurement cycle. If each of the steps has been not positively verified, a further pre-treatment process is impossible and, consequently, the appropriate analysis of the rock stress-strain characteristics.

### 3.1.1. Determining the parameters of the initial pin contact point P2

In real-life measurement conditions, the initial pin contact point P2, located on the chart of the measurement cycle results (Fig. 7) characterises the state of a physical contact of the pin with the borehole surface, simultaneously without exerting pressure on the tested rock surface (Fig. 4b). A basic purpose of determining this point's parameters is to verify whether any contact of the pin with the borehole wall has been achieved. However, from a point of view of carrying out the computer software assisted pre-treatment procedure, a main purpose of determining this point is to narrow the set of data among which the point of the full pin contact P4 and, subsequently, the point of the proper pin contact P3 could be determined.

It should be noted that it is virtually impossible to determine the parameters of the point of initial contact P2 without a prior knowledge of a behaviour of the penetrometer's unstrained pin stroke characteristics $p_{pin} = f(l_{pin})$, especially the static and the kinematic characteristics of the unstrained pin stroke.

The P2 point is defined as a pair of measured measurement parameters [$l_{\mathrm{P2}}$, $p_{\mathrm{P2}}$]. The initial pin contact stroke $l_{\mathrm{P2}}$ is such a first, lowest value of the recorded pin stroke $l_{meas}$ for which a corresponding pressure in the hydraulic system $p_{meas}$ equals to a sum of a corresponding values of a pressure from the static characteristics of the unstrained pin stroke $p_{stat}(l_{pin})$ and the maximum possible value of the kinematic pressure of the criterion of the end of the unstrained pin stroke $p_{kin\,\max}(l_{pin})$. Both pressure values $p_{stat}(l_{pin})$ and $p_{kin\,\max}(l_{pin})$ are derived from the unstrained pin stroke characteristics $p_{pin}(l_{pin})$ for $l_{pin}$ being equal to $l_{meas}$ (Fig. 6).

The parameters of the initial pin contact point P2 are defined as follows:

$$\mathrm{P2} = [l_{\mathrm{P2}}; p_{\mathrm{P2}}], \text{ where:} \tag{5}$$

$$l_{\mathrm{P2}} = \min l_{meas}, \text{ for } p_{meas}(l_{meas}) \geq p_{stat}(l_{pin}) + p_{kin\,\max}(l_{pin}) \text{ and for } l_{pin} = l_{meas} \tag{6}$$

$$p_{\mathrm{P2}} = p_{meas}(l_{\mathrm{P2}}) \tag{7}$$

However, due to requirements of next steps of the verification process (a determination of parameters of the full pin contact point P4 and the proper pin contact point P3), the parameters of the initial pin contact point P2 could be more conveniently determined on a basis of a reduced pressure data characteristics $p_{red} = f(l_{meas})$. This characteristics is made by subtracting the pressure values from measurement cycle characteristics $p_{meas} = f(l_{meas})$ with corresponding pressure values of the static characteristics of the unstrained pin stroke $p_{stat} = f(l_{pin})$ (Fig. 8), for each given pin stroke $l_{pin}$ being equal to $l_{meas}$:

$$p_{red}(l_{meas}) = p_{meas}(l_{meas}) - p_{stat}(l_{pin}) = (p_{pin} - p_{stat})(l_{meas}), \text{ for } l_{pin} = l_{meas} \tag{8}$$

Then, parameters of a so-called reduced point of the initial pin contact $P2_{red}$ are determined then as follows:

$$P2_{red} = [l_{P2}; p_{P2\,red}] \tag{9}$$

where:

$$l_{P2} = \min l_{meas}, \text{ for } p_{red}(l_{meas}) \geq p_{kin\,\max}(l_{pin}) \text{ and for } l_{pin} = l_{meas} \tag{10}$$

$$p_{P2\,red} = p_{red}(l_{P2}) \tag{11}$$

So, the initial pin contact point P2 described by the use of the parameters of the reduced point of initial pin contact point $P2_{red}$ is determined as follows:

$$P2 = P2_{red} + p_{stat}(l_{P2}) = [l_{P2}; p_{red}(l_{P2}) + p_{stat}(l_{P2})] \tag{12}$$

A graphical representation of the method of determining the reduced point of the initial pin contact $P2_{red}$ is shown in Fig. 8.

On the other hand, Fig. 11 shows the determined point P2 along with other determined points P3 and P4, in order to illustrate their position of these points in relation to the chart of the measurement results $p_{meas} = f(l_{meas})$.

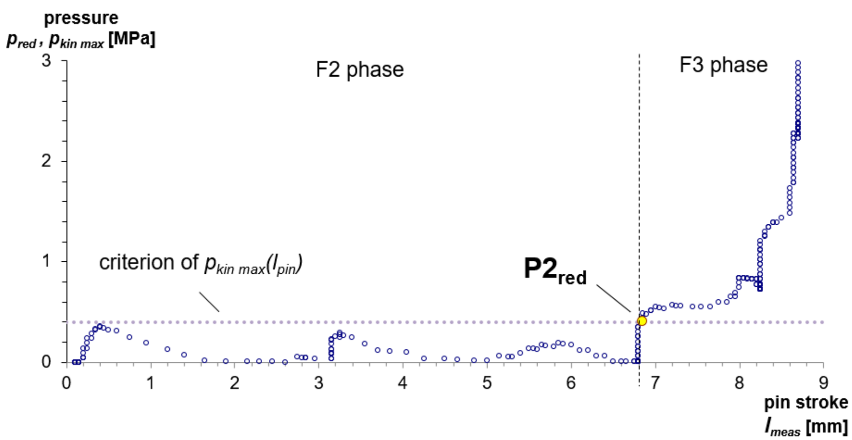


Fig. 8. A graphical representation of the determination of the reduced point of the initial pin contact $P2_{red}$

### 3.1.2. Determining the parameters of the full pin contact point P4

The full pin contact point P4 is a very important element of the measurement cycle results chart $p_{meas} = f(l_{meas})$. It separates results altered by the influence of the transitional stage, i.e. during setting of the head in the borehole (F3 phase), from results of the main stage (F4 phase) (Fig. 5). In other words, parameters of the full pin contact point P4 define the beginning of the useful data of the measurement cycle's main stage that will undergo the analysis of the rock stress-strain parameters after the pre-treatment procedure is done.

In real measurement conditions, due to the unknown course of the transitional stage, the parameters of the full contact point P4 cannot be determined directly. However, as a guide to determine this point, four assumptions have been made.

1. From the moment when the head and the pin assembly are fully set against the borehole wall (P4 point in Fig. 5), an increasing pressure on the rock surface is associated with a significant decrease of the pin stroke velocity, down to a negligible value. For such a slow pin stroke velocity, the nature of the friction forces acting during the pin stroke will be quasi-static, so the corresponding value of the maximum kinematic pressure $p_{kin\ \max}$, should be of 0.4 MPa (see Fig. 7).
2. As a consequence of aforementioned assumption, a slope of the measurement cycle data chart $p_{meas} = f(l_{meas})$ during the main stage of the cycle (phase F4) should be significantly higher than a slope during the transitional stage (F3 phase).
3. It was also assumed that an influence of a deformability of the penetrometer's head fully set in the borehole is negligible for an range of pressure values of a few MPa.
4. Due to the non-linear influence of the static characteristics of the unstrained pin stroke $p_{stat}(l_{pin})$ on the measurement cycle results, it is more convenient to analyse the measurement cycle data set without that influence. Hence, the reduced pressure characteristics $p_{red} = f(l_{meas})$, determined from eq. (8) is analysed. As a logical consequence, the parameters of a so-called reduced point of the full pin contact $\mathrm{P4}_{red}$ are determined first. The parameters of the full pin contact point P4 then can be determined with taking into account the influence of the static characteristics of the unstrained pin stroke $p_{stat} = f(l_{pin})$:

$$\mathrm{P4} = [l_{\mathrm{P4}}; p_{\mathrm{P4}}] \tag{13}$$

$$\mathrm{P4} = \mathrm{P4}_{red} + p_{stat}(l_{\mathrm{P4}}) = [l_{\mathrm{P4}}; p_{red}(l_{\mathrm{P4}}) + p_{stat}(l_{\mathrm{P4}})] \tag{14}$$

Considering above assumptions, a method of determination of the parameters of the reduced point of the full pin contact $\mathrm{P4}_{red}$ has been proposed. This method relies on an analysis of the slope of a processed reduced measurement characteristics $p_{red} = f(l_{meas})$. For this purpose, reduced pressure $p_{red}$ values for each measured pin stroke $l_{meas}$ value were mid-ranged, according to a formula:

$$p_{mid\ n}(l_{meas\ n}) = \left(\min p_{red}(l_{meas\ n}) + \max p_{red}(l_{meas\ n})\right)/2 \tag{15}$$

As an effect, a characteristics of the mid-ranged pressure as a function of the pin stroke (short: mid-ranged measurement characteristics) $p_{mid} = f(l_{meas})$ is obtained (Fig. 9).

Next, a linear regression analysis of a chosen range of mid-ranged pressure values is performed. The chosen range of this characteristics pressures should belong to the F4 phase of the measurement cycle. A lower limit of the selected range of the pressure results, from $p_{lin\ 1}$ to $p_{lin\ 2}$, was defined according to following formulas:

$$p_{lin\ 1} = p_{kin\ \max} + \Delta_1 \tag{16}$$

$$p_{lin\ 2} = p_{lin\ 1} + \Delta_2 \tag{17}$$

where:

$$\Delta_1 = 0 \div 3 \text{ MPa, typically 2 MPa} \tag{18}$$

$$\Delta_2 = 1 \div 3 \text{ MPa, typically 2 MPa} \tag{19}$$

A main goal with choosing the values of $\Delta_1$ and $\Delta_2$ coefficients is to find a linear trend line of a fragment of the $p_{mid} = f(l_{meas})$ chart that is describing (however not yet known) the initial fragment of the F4 phase. Values of the $\Delta_1$ and $\Delta_2$ coefficients should be chosen based on experience of a person conducting measurement data analyses of similar types of rocks. They also could be verified by observation of changes of the slope of the $p_{red} = f(l_{meas})$ chart (Fig. 9). For a purpose of a properly performed linear regression analysis, it is important that for a selected pressure range from $p_{lin\ 1}$ to $p_{lin\ 2}$, at least two $P_{mid}[l_{meas}; p_{mid}]$ points of mid-ranged pressure values could be found. The $p_{lin\ 2}$ pressure value should not exceed the pressure of the critical pressure point P5 (see Fig. 5).

Such a defined set of points from $P_{mid\ 1}$ to $P_{mid\ n}$ selected from the mid-ranged measurement characteristics $p_{mid}(l_{meas})$ data (between points $P_{lin\ 1}$ and $P_{lin\ 2}$) is subjected to a linear regression analysis. As a result, a linear trend function $p_{mid\ lin} = f(l_{meas})$ is determined in a form of a following equation:

$$p_{mid\ lin} = a \cdot l_{meas} + b \tag{20}$$

where: $a$, $b$ – coefficients of the linear trend line.

The reduced point of the full pin contact $P4_{red}$ is a so-called point close enough to the trend line $p_{mid\ lin} = f(l_{meas})$. A close-enough point term means that the difference between this point's mid-ranged pressure value and a corresponding pressure deducted from the linear trend line for $P_{mid\ 1}$ to $P_{mid\ n}$ points is lower than a chosen threshold value $\Delta_3$ (assumed to be 0.5 MPa for the

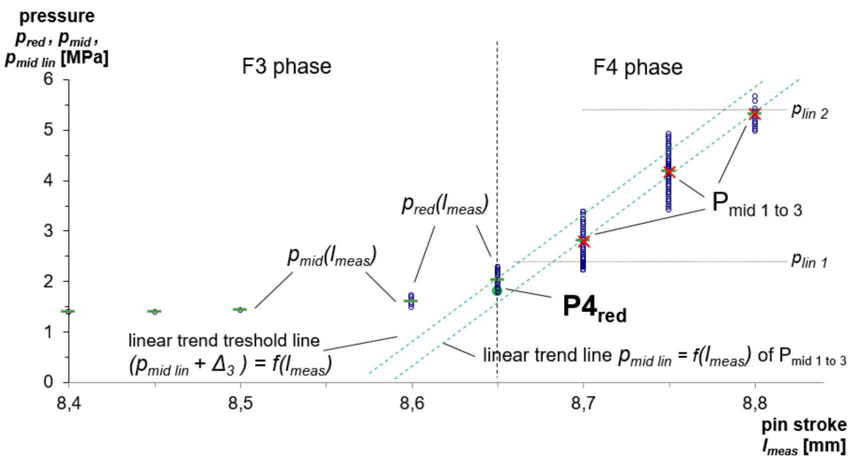


Fig. 9. A graphical representation of the determination of the reduced point of the full pin contact $P4_{red}$

analysed measurement cycle data set). The parameters of the reduced full contact point $P4_{red}$ are determined from following equations:

$$P4_{red} = [l_{P4}; p_{P4\,red}], \tag{21}$$

where:

$$l_{P4} = \min l_{meas}, \text{ for } p_{mid}(l_{meas}) \le p_{mid\,lin}(l_{meas}) + \Delta_3 \tag{22}$$

$$p_{P4\,red} = \min p_{red}(l_{P4}) \tag{23}$$

Again, if the parameters of the reduced point of the full pin contact $P4_{red}$ cannot be determined, it means that it is not possible to obtain the set of useful results from the performed measurement cycle and there is no purpose for performing further stages of the pre-treatment of the measurement cycle results.

### 3.1.3. Determining the parameters of the appropriate setting of the penetrometer's head

In case of positive verification of achieving a state of full contact of the pin (section 3.1.2), parameters of the appropriate setting of the penetrometer's head for the measurement cycle are determined by parameters of the proper pin contact point P3. These parameters, in turn, are determined on a basis of the parameters of a so-called reduced point of the proper pin stroke $P3_{red}$.

$$P3 = [l_{P3}; p_{P3}] \tag{24}$$

$$P3 = P3_{red} + p_{stat}(l_{P3}) = [l_{P3}; p_{red}(l_{P3}) + p_{stat}(l_{P3})] \tag{25}$$

The reduced point of the proper pin stroke $P3_{red}$ is determined as the intersection point of the value of the trend line of the criterion of the maximum possible increase of the kinematic pressure $p_{kin\,\max}(l_{pin})$ for the quasi-static conditions of the pin stroke velocity (having in fact the same value as the criterion of the reduced point of the initial pin contact $P2_{red}$ – see section 3.1.1) and the extrapolated trend line of the selected data interval of the mid-ranged fragment of the reduced measurement characteristics $p_{mid\,lin} = f(_{meas})$ (20) (see section 3.1.2).

$$P3_{red} = [l_{P3}; p_{P3_{red}}] \tag{26}$$

where:

$$l_{P3} = (p_{mid\,lin} - b)/a \tag{27}$$

$$p_{P3_{red}} = p_{kin\,\max}(l_{pin}) \tag{28}$$

Assumptions of the proposed method:

- during the phase of setting the head in the borehole (phase F3), the rock has the same value of modulus of deformation as in the initial part of the main stage (phase F4),
- an influence of the head deformation during the phase F3 (i.e. between the point P3 and point P4 of the measurement cycle) is negligibly low.

The described method is represented graphically in Fig. 10.

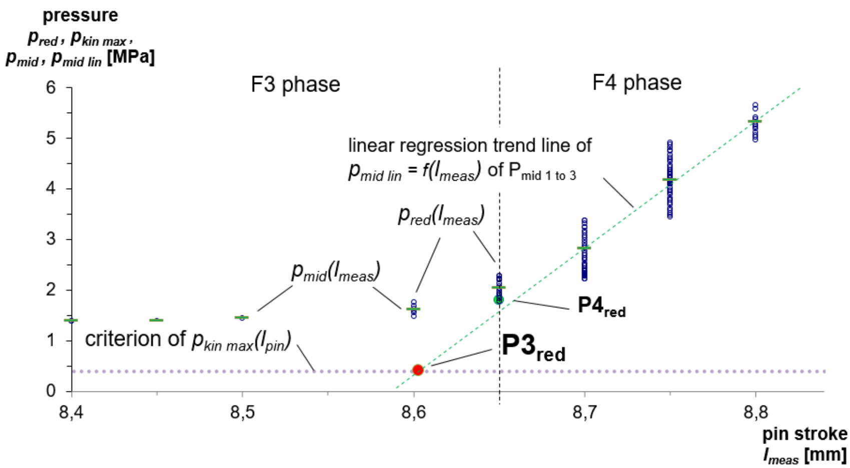


Fig. 10. A graphical representation of the determination of the reduced point of the proper pin contact $P3_{red}$

## 3.2. Application of the adjustment of the hydraulic pressure values based on the operational characteristics of the penetrometer

The parameters of the proper pin contact point allow for an appropriate application of adjustments for the measured pressure $p_{meas}$ and pin stroke $l_{meas}$ values. In effect, an effective pressure $p_{eff}$ and an effective pin stroke $l_{meas}$ values can be determined.

The effective pressure exerted by the pin on the borehole surface $p_{eff}$ is one of two main parameters required to analyse the rock mass stress-strain parameters. To obtain a set of the effective pressure data, each measured hydraulic pressure value should be subtracted by a corresponding pressure value of the proper pin contact point, $p_{P3}$ and multiplied by a ratio of the piston assembly working surface area $A_{piston}$ and the pin face $A_{pin}$:

$$p_{eff}(l_{meas}) = \left(p_{meas}(l_{meas}) - p_{P3}\right) \cdot (A_{piston} / A_{pin}),\ \text{for}\ l_{meas} \geq l_{P4} \tag{29}$$

## 3.3. Significance of the new pre-treatment method results for preparing a useful data set for the rock stress-strain analysis

The graphical representation of the determined points P2, P3 and P4 on the background of the analysed measurement cycle data chart is shown in Fig. 11.

These three points were determined on the base of the static characteristics of the unstrained pin stroke $p_{stat} = f(l_{meas})$ and the parameters of the reduced points $P2_{red}$, $P3_{red}$ and $P4_{red}$, using equations (12), (14) and (25). It can be observed that the proper pin contact point P3 isn't located on the measurement cycle data chart, but rather outside it (see also Fig.4). The appropriate determination of such a point could be not possible without a prior verification steps of the measurement cycle data pre-treatment, including the use of the operational characteristics of the penetrometer's head.

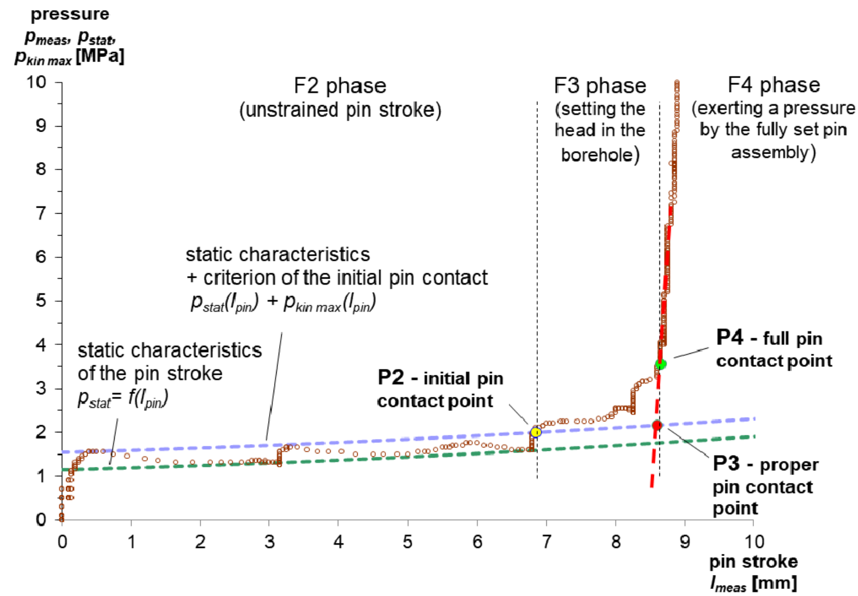


Fig. 11. A graphical representation of the determined points P2, P3 and P4, the operational characteristics $p_{pin} = f(l_{pin})$ and the criterion of the end of the unstrained pin stroke $p_{kin\,\max}$

Comparing the new method to a mentioned earlier, widely known criterion of a pressure/stress/force threshold value (see section 2), it is clear that an arbitrary setting of such a pressure threshold value without the knowledge of the operational characteristics and a unknown span of the measurements cycle's transitional stage (the F3 phase) could even lead to an unreliable results, especially for the purpose of the effective pin stroke determination.

For a purpose of a comparison of threshold value method and the new method of determining the beginning of the set of the useful results, two examples of an arbitrarily chosen pressure threshold values were chosen.

As a first example, an arbitrary pressure threshold value of 2.25 MPa has been chosen. For such a threshold value a possible pin stroke on the measurement cycle chart (Fig. 11) ranges from 7.25 mm to 7.65 mm. Comparing this range of results to a determined value of the proper pin contact point $p_{P3}$ = 8.60 mm and to a typical range of observed rock deformation span of ca. 0.5÷2 mm, it is clear that the difference of both pin stroke values (0.95 to 1.35 mm) could have a significant impact for the purpose of determining the effective pin stroke and subsequent rock stress-strain analysis.

As a second example, an arbitrary pressure threshold value of 4.0 MPa has been chosen. For such a threshold value, a corresponding pin stroke of 8.65 mm is very close to the determined pin stroke value of the proper pin contact $l_{P3}$ = 8.60 mm. However, adjustments of the measurement cycle readouts by 4.0 MPa, compared with adjustments by the determined pressure of the proper pin contact point $p_{P3}$ = 2.16 MPa of the new proposed method for a typical critical pressure for weak rock of ca. 5÷10 MPa, again shows a high difference of the final results.

The relative differences of results for both examples have even more significance for low strength rocks, as mentioned at a beginning of this section.

## 4. Summary and conclusions

An appropriate extraction of useful results set from the recorded *in situ* measurement cycle data is one of the main issues of the interpretation of measurement cycle results. In order to be able to obtain a high confidence of the useful results set extraction it is needed to properly prepare the measuring device for the measurement cycle and to know the influence of the device on the parameters readouts.

However, in case of various field test methods, the penetrometric method being an example, it is often difficult to properly prepare and stabilise the device for the measurement cycle. As a consequence, a some part of the measurement cycle data could be altered in an undetermined way, making it difficult to determine the parameters of the beginning of the useful data set. An inadequate determination of the beginning of the useful data set may have a significant impact on results of the rock behaviour analysis, in a form of a disturbed or even lost initial fragment of the stress-strain characteristics of rock.

The implementation of hardware and firmware modifications to the standard Pen206 borehole penetrometer allowed for an extended analysis of the specifics of the measurement cycle process and various factors influencing the values of the measured parameters. This let to determine the operational characteristics of the new Pen206_18 device and the so-called stiffness of the pin assembly. More, by taking some assumptions about the nature of rock deformability under low stress and by considering the influence of the operational characteristics of the penetrometer, it was possible to develop a method of determining three characteristic parameters of the transitional stage of the measurement cycle characteristics.

To determine the effective value of the pressure of the pin on the rock, expressed in units of the equivalent hydraulic pressure exerted on the piston, it is needed to apply the adjustment resulting from the operational characteristics of the penetrometer and the ratio of the surface areas of the piston assembly and the pin. This adjustment value depends on the pin stroke values.

In order to accelerate and automate the pre-treatment process of measurement results, a procedure of pre-treatment of pressure measurement results has been developed, in a form that can be implemented in a computer analytical software. The procedure allows for possible future adjustments of some yet unknown criterions, according to, for example, performing measurement cycles under various field conditions, like the rock mass temperature.

The presented aspects of measurement cycle data pre-treatment of the penetrometric method could be helpful to increase the accuracy of interpretation of the measurements results obtained by other new static type methods of measurements of strength or stress-strain parameters of rocks, especially where the appropriate setting of the measuring device is difficult and the amount of measurement cycles is significant.

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