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Arch. Min. Sci. **65** (2020), 3, 569-590

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2020.134135

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A PEN206 BOREHOLE JACK SUITABILITY ASSESSMENT FOR ROCK MASS DEFORMABILITY DETERMINATION

Currently available field rock mass deformability determination methods are rather difficult to perform, due to their complexity and a time-consuming nature. This article shows results of a suitability assessment of a Pen206 borehole jack (a hydraulic penetrometer) for field rock mass deformability measurements. This type of the borehole jack is widely used in Polish hard coal mining industry. It was originally intended only for quick rock mass strength parameters determination. This article describes an analysis and scope of basic modifications performed mainly on a borehole jack head. It includes discussion of results with possible directions for future development of the device.

Keywords: borehole, jack, rock, deformability, assessment, test

1. Introduction – research goal and currently available measuring equipment

A main act of a Polish law that regulates issues related with mining activities, i.e. The Act from 9th June, 2011 – Geological and Mining Law (together with the Ordinance of the Minister of Energy of 23rd of November, 2016), imposes the obligation of determining various geomechanical properties of rock mass for a purpose of an underground openings support design.

Two basic geomechanical factors describing behaviour of rock mass subjected to load are rock deformability and an ultimate rock strength. However, certain deformability parameters cannot be determined without reaching the ultimate rock strength. Thus, a valuable way of de-

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termine rock mass deformability parameters would be by a method which can also be used to determine rock strength parameters.

So far, the only method used to determine rock strength and deformability in Polish hard coal mines is a laboratory triaxial testing of rock samples (according to interviews with various Polish coal mines representatives and to [Kidybiński, 1982]). However, this method not always can be used, due to various technical or organisational reasons. For example, a preparation of appropriate rock samples for this type of test can often be problematic. It could be caused by a low rock cohesion or a high rock mass fracturing [Palmström & Singh, 2001; Bukowska & Kidybiński, 2002].

Alternatively, using a field method of determining rock deformability could be a better solution of determining geomechanical parameters of weak rocks than the laboratory triaxial testing. In fact, a necessity of obtaining field rock deformability parameter values arose during carrying out of various projects by the Central Mining Institute, Katowice. These projects were related to the stability of underground workings driven in weak rock strata of the Upper Silesian Coal Basin (Westphalian C and D). These rocks (mainly sandstones with weak clay cementation) were characterised by a very low cohesion, which often prevented the preparation of appropriate core samples to conduct laboratory testing of rock deformability and ultimate compressive strength.

Unfortunately, there is no field method of determining rock deformability ready to be easily implemented in the Polish hard coal mines. Admittedly, a few static type field methods are popular in the foreign scientific literature, for example the plate jacking test – PJT, the plate loading test – PLT or the Goodman jack test (Fig. 1) [Goodman & Shi, 1968; Palmström & Singh, 2001; Heuze, 2003; Zhang, 2017]. Meanwhile, many geomechanical rock mass parameters measurements in the Polish hard coal mines are required to be performed in the vicinity of nearby active mining operations. Therefore, an amount of effort related with a preparation of a test site or doing measurements of aforementioned field methods could frequently collide with a mining activities schedule. An example could be simply a blockage of supply transport pathways. Besides, measurement cycles of these methods also involve significant financial costs.

So far, the only one frequently used field method of determining some of the geomechanical properties of rocks in the Polish hard coal mines is a borehole jack test [Kidybiński et al., 1976, Nierobisz, 2010; Nierobisz et al., 2016]. This static type measurement method was developed to determine some of the rock mass strength parameters only. Unfortunately, this method is rather still unknown in a foreign scientific literature.

At present, the determination of additional rock mass geomechanical parameters, like the modulus of deformability, would require a separate measuring equipment and an additional amount of time and effort than to perform borehole jack rock mass strength tests only.

As it was mentioned at the beginning of this article, some static methods of determination of rock mass strength and deformability in fact do share similar characteristic. It relies on exerting a force on a rock surface and observing such effects as a rock deformation or a destruction of a rock structure. This observation let the authors of this article to conclude that for the purpose of determining deformability of rock mass in the Polish hard coal mines it could be reasonable rather to expand metrological properties of an existing rock strength apparatus instead of using another separate rock mass deformability measuring set. This conclusion could be achieved by a modification of a well-known in the Polish hard coal mines Pen206 type hydraulic borehole jack [Nierobisz, 2010]. This type is a newer version of an original PHI-00 type borehole jack, a tool which has been in use for over forty years to determine rock mass strength parameters. The PHI-00 type borehole jack was developed in the Central Mining Institute, Katowice,

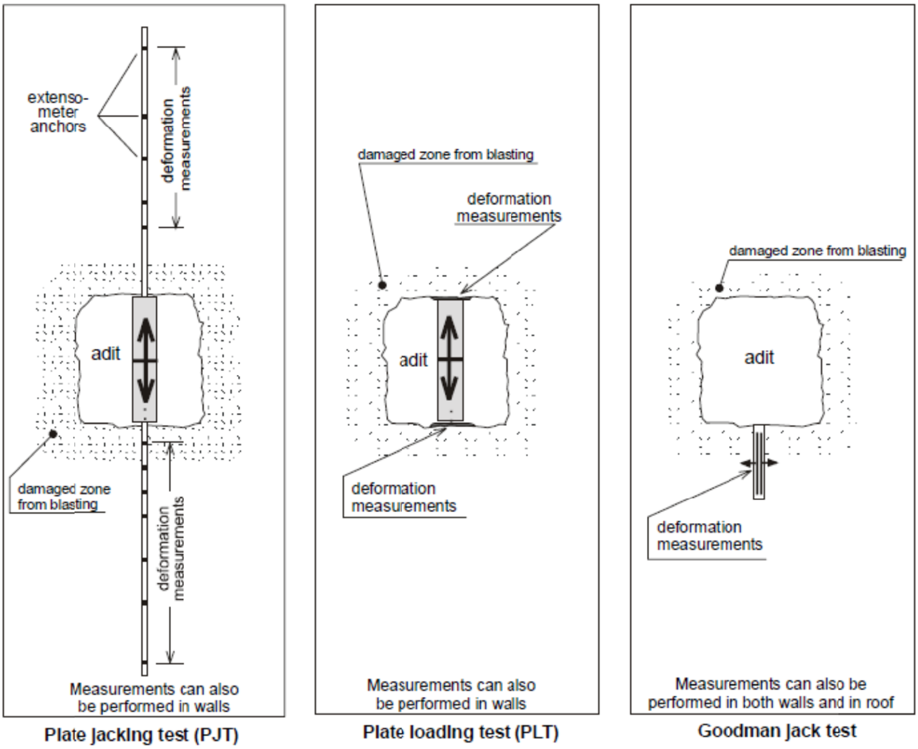


Fig. 1. Comparison of three in situ static test method types. Per: Palmström and Singh, 2001

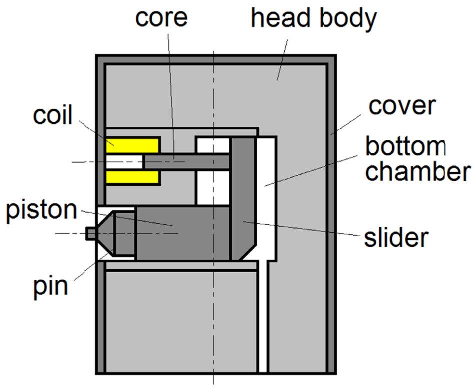
Poland [Kidybiński et al., 1976]. A borehole jack test procedure isn't colliding much with mining activities and test requirements (drilling of a 95 mm diameter borehole) are relatively easy to fulfil.

Using the modified Pen206 jack in a rock mass test could bypass the limitations of laboratory method requirements described above in this section, by providing measurements at virtually any point in the drilled rock strata. Furthermore, the test would involve the relatively faster preparation of the test site than the PJT or PLT methods. More, the test would provide more detailed characteristic of rock mass deformability than the Goodman jack test.

Hence, a main goal of the assessment of the Pen206 jack method was to determine a capability to expand its metrological properties.

2. The standard Pen206 borehole jack characteristic

A main principle of operation of the Pen206 borehole jack is identical to the original PHI-00 jack [Kidybiński et al., 1976] and is based on exerting an increasing radial force on a HQ size (90-100 mm diameter) borehole wall by a piston tipped with a tapered cylindrical-conical pin. The piston with the pin move out from an 85 mm diameter cylindrical jack head. A general borehole jack head structural diagram is presented in Figs. 2a and 2b.



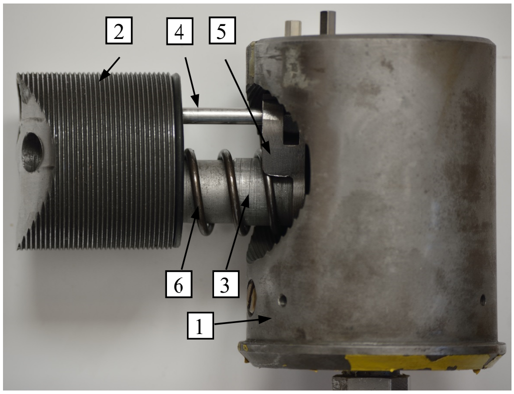


Fig. 2. a) the general structural diagram of the Pen206 hydraulic borehole jack head, b) a photo of the head assembly (without a jack head cover): 1 – head body, 2 – slider base, 3 – piston, 4 – coil's core, 5 – slider, 6 – return spring

The piston (and the pin) stroke is caused due to increasing hydraulic pressure in a bottom chamber of the head. The head is connected with a hydraulic hand pump by a 15 m long hydraulic hose. The jack head has also a socket for screwing in a set of pushing rods needed to insert it into the borehole at a desired measurement depth. A change of depth of the jack head in the borehole between each following measuring cycles is 0.1 m and a typical length of the examined borehole is 10 m. The borehole jack has also a control panel, which has an analogue-to-digital converter to process the electrical signals from the pin stroke transducer located in the jack head and the hydraulic pressure transducer located in the hydraulic pump assembly. The control panel also has a digital memory bank to store recorded parameter values, a built-in LCD display and a keyboard for setting measurement conditions.

A result of a standard borehole jack test is a critical pressure $p_{n\ crit}$ obtained in a hydraulic system. This pressure value corresponds to a maximum force that can be radially exerted on a surface of borehole wall without causing a damage of a rock structure. In practice, this critical pressure $p_{n\ crit}$ is possible to determine only by causing a dynamic destruction of the rock mass structure (crushing). An effect of this process is a pin insertion (penetration) into a generated cavity (crater) in the borehole wall.

A relationship between the critical pressure and the rock mass unconfined compressive strength (*UCS*) is as follows:

$$UCS = a \cdot p_{n\ crit} \tag{1}$$

where: a – a compressive strength coefficient factor.

Based on recent research [Bukowska & Kidybiński, 2002], an original average value of the coefficient factor a = 1.2 for has been adjusted to a = 1.0.

The original PHI-00 jack used a pressure gauge. The Pen206 generation of the hydraulic borehole jack, developed in 2008 [Nierobisz, 2010; Nierobisz et al., 2016] is equipped with an electronic pressure transducer and the analogue-to-digital converter. This allows to measure and store the critical pressure values in a digital memory bank with additional data, such as the head depth in the borehole.

It should be noted that the Pen206 borehole jack was designed also to measure the pin stroke. The borehole jack makes use of a magnetoelectric method of the pin stroke measurement. The pin stroke transducer consists of a coil and a movable core. The core is coupled mechanically with the piston by a slider.

However, a main purpose of the pin stroke measurement was to inform an operator control panel if the pin draws back correctly into the head after the end of measurement cycle. Another use of the pin stroke measurement was to detect a locally too large borehole diameter unsuitable for testing. A such state is determined through a maximum pin stroke reached at the very beginning of the measurement cycle. Finally, the pin stroke measurement was an indicator of a broken pin. When a pin tip breaks, a longer than usual (by approximately 5 mm) jacked pin stroke is observed and the broken pin has to be replaced by a new one.

3. A scope of the Pen206 borehole jack suitability assessment

A four main aspects of the borehole jack assessment were determined first:

- to determine if the Pen206 borehole jack has the metrological specification adequate to the prospective range of the measured parameter values,
- to examine the construction and influence of the jack head mechanical properties on the parameter readouts,
- to verify if the borehole jack equipment has the capability to record the measurement data with a proper rate during a whole measurement cycle time,
- to indicate what should be done to fulfil the three aforementioned aspects and what could be possible to improve in a future development.

For the purpose of the Pen206 borehole jack suitability assessment for rock deformability determination, a few assumptions about principles of measurement has to be drawn first.

Initially, it was assumed that a rock deformability could be represented by a radial borehole wall deformation $\Delta l_{borehole}$, which in turn is equivalent to a stroke increase of the pin Δl_n that exerts a force on the borehole wall.

$$\Delta l_{borehole} = \Delta l_n \tag{2}$$

It was also assumed that a pin and piston deformability is negligible. Then, the pin stroke increase Δl_n is equivalent to a transducer's core stroke increase Δl_c (Fig. 1).

$$\Delta l_n = \Delta l_c \tag{3}$$

The pin stroke increase is calculated from the point the pin achieves proper contact with the borehole wall from a following equation:

$$\Delta l_n = l_n - l_{n0} \tag{4}$$

where:

l_n — an ongoing stroke of a pin [mm],

l_{n0} — a stroke of a properly jacked pin against borehole wall [mm].

For a current stage of the assessment of the borehole jack which has been described in this paper, it was assumed that the properly jacked pin stroke l_{n0} is a maximum pin stroke, for which the hydraulic pressure p_n equals to 0. However, a certain pressure value is needed to obtain a certain pin stroke, by overcoming a force of a return spring of the piston. A correlation between these two parameters is described as a jack head performance characteristic. The performance characteristic is needed to adjust the pressure readings. However, discussing an issue of the determination of the jack performance characteristic is beyond the scope of this article, as it was possible to perform only in a next stage of a Central Mining Institute's statutory work, also devoted to the assessment of the suitability of the borehole jack.

A real borehole diameter is calculated as follows:

$$D_0 = D_H + l_{n0} \tag{5}$$

where:

D_H = 85.0 mm — a borehole jack head diameter,
l_{n0} — properly jacked pin stroke [mm].

The main rock mass deformability parameter to be determined on the measurement results is then a radial borehole strain $\varepsilon_{borehole}$:

$$\varepsilon_{borehole} = \Delta l_n / D_0 \tag{6}$$

Based on equations (2), (4) and (5), the radial strain of the borehole wall $\varepsilon_{borehole}$ is calculated then as follows:

$$\varepsilon_{borehole} = \varepsilon_n = (l_n - l_{n0}) / (D_H + l_{n0}) \tag{7}$$

3.1. The assessment of the borehole jack measurement properties

A first issue of the borehole jack suitability assessment was, if its standard pin stroke measurement section is able to reliably measure the borehole wall surface deformation, and if it isn't, what can be then improved in this matter.

A deformability measurement specification of the borehole jack was compared to the 'Suggested methods for determining uniaxial compressive strength and deformability of rock materials' guideline of the International Society for Rock Mechanics [ISRM, 1979]. In fact, this guideline is related mainly to perform laboratory uniaxial tests on rock samples. Nevertheless, the guideline could be considered as a starting point for the assessment of the borehole jack suitability.

First, the ISRM guideline recommends measurement of a rock strain with an accuracy within 2% of a readout.

Assuming that the borehole diameter D_0 has a constant known value and an influence of its measurement error is negligibly small in comparison to an influence of the pin stroke measurement error, the measured rock strain relative accuracy *acc.* ε_n is determined from this equation:

$$\begin{aligned} acc.\ \varepsilon_n &= (\varepsilon_n - \varepsilon_R) / \varepsilon_R = (\Delta l_n / D_0 - \Delta l_R / D_0) / (\Delta l_R / D_0) = \\ &= (\Delta l_n / \Delta l_R - 1) \cdot 100\ [\%] \end{aligned} \tag{8}$$

where:

ε_R — the real pin stroke strain [‰],
Δl_R — the real pin stroke [mm].

If a difference between Δl_n and Δl_R equals to ±1 discrete measurement resolution value, then:

$$acc.\ \varepsilon_n = (\Delta l_R \pm 1\ discrete) / \Delta l_R - 1 = 1\ discrete / \Delta l_R \cdot 100\ [\%] \tag{9}$$

A digital measurement resolution (the 1 discrete) of the standard CZP v0.1 pin stroke transducer was 0.1 mm within a pin stroke range from 5 mm to 18 mm (i.e. for measurements in HQ size boreholes of 90 mm to ca. 100 mm diameter).

A minimal pin stroke increase Δl_R min, to be able to be measured with ISRM's given measurement's *acc.* ε_n = 2% for the standard pin stroke transducer's discrete resolution of 0.1 mm, is as follows:

$$\Delta l_{R\,\min} = 1\ discrete / acc.\ \varepsilon_n = 0.1\text{ mm} / 0.02 = 5\ [\text{mm}] \tag{10}$$

However, experience gained during in situ testing of the rock strength parameters with the standard Pen206 borehole jack allowed to draw a following observation: a significant number of measurement cycles is characterised by a pin stroke increase Δl_n of lower than 1 mm (sometimes up to 2 mm), estimated from the point the pin is correctly jacked against the borehole wall surface.

So, based on equation (10) to be able to measure the pin stroke increase of 2 mm within an expanded pin stroke measurement range from 3 mm to 18 mm with recommended ISRM's accuracy of 2 %, a required pin stroke transducer's resolution should be of 0.04 mm.

Second, the ISRM guideline recommends also measurement of a rock strain with a precision of 0.2% of a full scale.

The precision of the measurement, *prec.* ε_n is calculated as:

$$prec.\ \varepsilon_n = 1\ discrete / \Delta l_{R\,\max} \cdot 100\ [\%] \tag{11}$$

where: $\Delta l_{R\,\max}$ – a maximal real (measurable) pin stroke increase [mm],

$$\Delta l_{R\,\max} = l_{R\,\max} - l_{R\,\min} \tag{12}$$

For a standard real measurement range of the pin stroke l_R = 5 – 18 mm,
$\Delta l_{R\,\max}$ = 18 mm – 5 mm = 13 mm

So, the real precision of the measurement *prec.* ε_n, *for* the standard pin stroke transducer's discrete resolution of 0.1 mm is calculated as follows:

$$prec.\ \varepsilon_n = 0.1\text{ mm} / 13\text{ mm} \cdot 100\ \% = 0.77\ \%\text{ of the full scale} \tag{13}$$

Obtained measurement precision is worse than recommended ISRM's value of 0.2%. So, based on equation (13), and recommended ISRM's measurement precision, within the expanded pin stroke measurement range from 3 mm to 18 mm, a required pin stroke's resolution should be better than 0.03 mm.

To summarise, to fulfil both of the recommended ISRM's measurement accuracy and precision, the required minimal resolution of the pin stroke measurements, for the expected range of pin stroke increase of 2 mm in the expanded pin stroke measurement range of 3-18 mm, the minimal pin stroke's transducer should be better than 0.03 mm.

It should be noted again that ISRM's guideline was proposed for laboratory testing. It is conceivable that field testing of rock mass deformability could be performed in worse measurement conditions than laboratory testing, so other factors could also influence the measurement quality.

After comparing these observations with the ISRM guideline, the authors concluded that the existing resolution and precision of the pin stroke measuring equipment in the borehole jack head may be insufficient to obtain reliable data set for the rock deformability analysis.

However, a further analysis of the Pen206 borehole jack head design found that for the current stage of the borehole jack suitability analysis it was possible to improve the resolution of pin stroke measurements, by modifying a standard CZP v0.1 type pin stroke transducer. A modified pin stroke transducer CZP v0.2 type was characterised by 0.05 mm digital measurement resolution, which was twice as high than the resolution of the standard Pen206 pin stroke transducer. More, a modified transducer's pin stroke measurement linearity range has been increased to 2-18 mm. For given parameters, based on equations (10) and (13), the measurement accuracy was calculated to be 2.5% and the precision to be 0.31% of the full scale, within the pin stroke measurement range from 5 mm to 18 mm.

Such measurement resolution should be adequate for preliminary field tests in order to observe the real rock mass deformability measurements range.

However, in the future, to be able to measure as low pin stroke increments as 1 mm within the expanded pin stroke measurement range of 3 to 18 mm, with the recommended accuracy of 2% and precision not worse than 0.2 % of the full scale, based on equations (10) and (13), the required pin stroke transducer's resolution should be of 0.02 mm.

3.2. The assessment of the borehole jack mechanical properties

The second issue of the borehole jack suitability assessment was to determine an influence of the borehole jack mechanical properties on the measurement readout values.

A borehole jack head structural and operational analysis showed that during the jacking of the pin against the borehole wall, some parts of the head could be deformed. It should be noted that a jack head parts deformation may result in a alteration of the pin stroke values measured by the pin stroke transducer, as the jack head deformation is related to a change of a real position of a pin stroke measurement reference point. Thus, it cannot be omitted for the purpose of proper measuring of the rock mass deformation parameters. A similar phenomenon could be found in scientific literature concerning other deformability measuring equipments [Swolfs & Kibler, 1982, for example] with attempts to correct a measurement discrepancy. Besides, it should be noted that the head deformability wasn't an issue in an original concept of borehole jack rock strength measurements, as the only measured parameter was simply the critical hydraulic pressure.

Therefore, a goal of the borehole jack head structural analysis was to define types of factors influencing the head deformability (e.g. head parts mechanical properties and structural clearances between them) and to determine which of them could be eliminated by means of jack head design modifications, and which should be compensated by applying empirical corrections for the readout values. An essential part of the modification process was to conduct bench testing with a purpose of determining the pin stroke readout correction.

In order to examine a result of the pin stroke transducer modification, bench tests were conducted for two borehole jack heads, one equipped with the standard pin stroke transducer, and another one equipped with the modified transducer.

A third stage of the borehole jack suitability assessment was intended to examine a possibility to develop a recording system for the jack control panel that would store the measured hydraulic pressure and the pin stroke readouts in a digital memory bank. An additional recorded parameter should be a time stamp of each parameter readout. The recorded values of these parameters should then be able to be exported to a computer and analysed using software tools. This stage is described in the 3.3. section of this article.

A fourth, final stage of the borehole jack suitability assessment was to draw directions of possible future development of the equipment. These directions are presented in a "Conclusions" section of this paper.

3.2.1. The bench test of a borehole jack head

The purpose of bench testing of the borehole jack head was to assess the influence of the borehole jack mechanical properties on the measurement readout values. This was done by comparing the measurement results given by the modified pin stroke transducer with the real position of the pin, measured by means of an external transducer. A result of this comparison is a stiffness characteristic of the jack head. By determining this characteristic it could be possible to apply a correction for each readout value of the jacked pin stroke.

A bench testing procedure was based on placing the borehole jack head in a measuring block (Figs. 3 and 4) and performing a cycle of pin jacking. A head stiffness test equipment was comprised of the steel measurement block (1) with a press bolt (2), placed on a stand with a mounted linear displacement transducer (3).

A main assumption related to the bench test was that the real jacked pin stroke increase equals to a change of the measurement block height. A second assumption relied on that the head parts behave mechanically like a spring. A third assumption was that a deformation of the steel

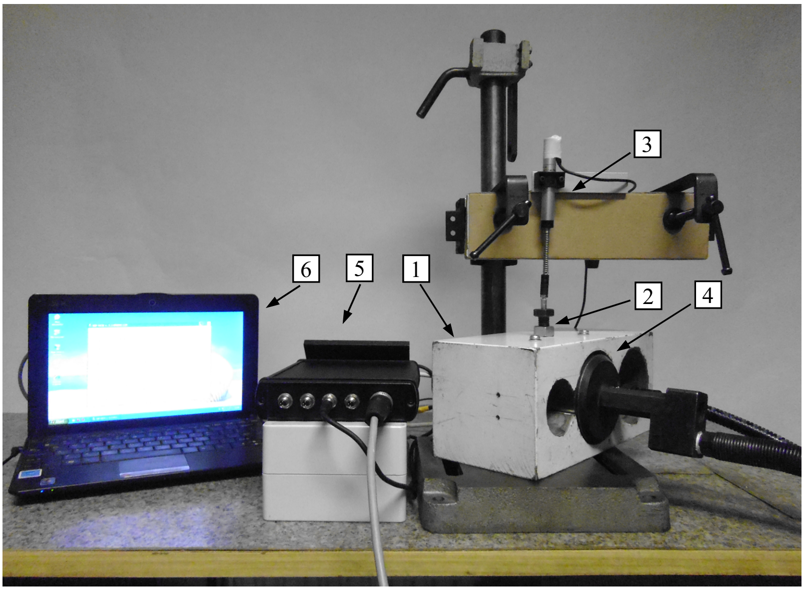


Fig. 3. The head stiffness test setup configuration. 1 – measurement block, 2 – press bolt, 3 – displacement transducer (block deformation measurement), 4 – borehole jack head, 5 – MADC-06 converter, 6 – PC

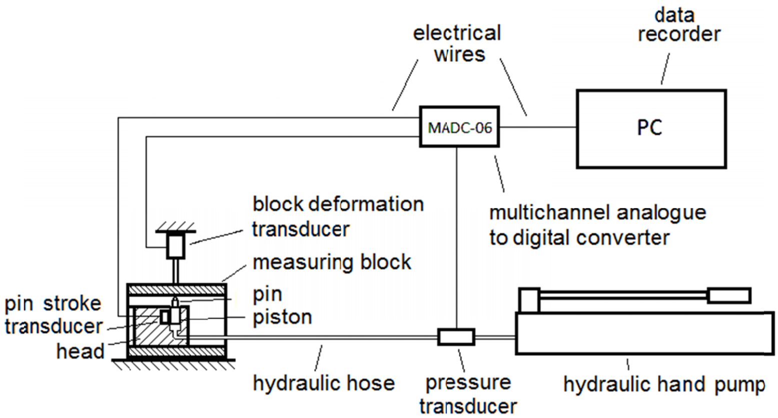


Fig. 4. A block diagram of a Pen206 borehole jack head stiffness measurement

press bolt (made of steel of 10.9 class and 330HV hardness) and a deformation of the pin (made of through-hardened tool steel) as well as a bolt thread clearance inside the block are negligible. More, it was expected that other head elements could undergo a deformation during jacking of the pin against a block internal opening surfaces.This phenomenon could be caused by, among others, an existence of some structural clearances within the jack head body. It should therefore be expected that the jacked pin stroke measurement taken by the pin stroke transducer in the head may be bigger from the one taken by the external transducer.

The measurement block (1) was formed from a standard quality St5 structural steel (EN: S235JR). Dimensions of the block were 250x110x110 mm. The block had three cylindrical openings, where a central one had a diameter of 88 mm and was intended to hold the borehole jack head inside (4), whereas two side openings were intended to hold cylindrical rock samples of two diameters: up to 78.0 mm or 48.5 mm, for prospective additional bench testing. The M12x1.5 press bolt (2) was screwed into a threaded opening in the block.

The purpose of utilising the bolt was to obtain a full contact with a flat pin face surface and to prevent the occurrence of plastic deformations in the block during jacking of the pin. The press bolt was made of class 10.9 hardened and tempered low-alloy steel with a hardness of 330HV. The stiffness of the measurement block reflected to some degree a range of pin stroke increase in a typical borehole jack field test.

The block was mounted in the stand in such a way so that an external transducer's (3) slider displacement axis overlapped with an axis of symmetry of the press bolt (2) and borehole jack pin.

Advantages of such test setup are: a structural simplicity and a possibility of conducting stiffness tests on demand, for example after a head maintenance service.

3.2.2. A measurement method and procedure

A goal of the measurement method was to be able to accurately measure a real pin position. This was provided by assumption that a pin stroke change of position from a point of contact with the press bolt of the measurement block is equal to a change of a measurement block height.

The measurement method was based on recording following parameters during jacking of the pin inside the measuring block:

1. p_n – a pressure in the borehole jack hydraulic system [MPa],
2. l_n – the pin stroke (measured by the transducer in the jack head) [mm],
3. l_B – the block height (measured by an external transducer) [mm],
4. t_n – a time stamp of the measurement readout [ms].

The hydraulic pressure measurement was done by the standard borehole jack pressure transducer located by the hydraulic pump assembly. The borehole jack pressure transducer had a measurement basic error of 0.2% of the full scale in a measuring range of 0-100 MPa. The pin stroke measurement was conducted by the transducer in the jack head. The external displacement transducer used in the block deformation measurement had a measurement linearity of 0.05% of the full scale in a measuring range of 0-25 mm.

All three transducers were connected to a MADC-06 analogue-to-digital converter (5) inputs. The MADC-06 converter was designed and produced exclusively for the Pen206 jack by Novaster and SilLog companies, Zabrze, Poland. These companies also designed and produced the measuring equipment of the standard Pen206 borehole jack. A data sampling rate of the MADC-06 converter was set to 200 readouts per second – in other words, a time interval between each subsequent parameter readouts was 5 ms. The converter had an input for digital measurement values from the standard or modified pin stroke transducer. The converter was processing an analogue signal from the external transducer of the block deformation measurement to a digital values with a resolution of 0.0125 mm, and an analogue signal from the pressure transducer with a resolution of 0.05 MPa. This 0.05 MPa resolution was two times higher than the standard borehole jack pressure converter's, located in the jack control panel.

The MADC-06 converter was able to transmit measured data via USB interface to a PC computer (6) running with SBP View recording software in Windows operating system (Fig. 2). The SBP View software was used to save the received readout values in the computer's non-volatile memory.

The bench test measurements were conducted mainly for the borehole jack head equipped with the modified pin stroke transducer. The borehole jack head with the standard pin stroke transducer was also tested, just to justify a decision of pin stroke transducer modification.

The point of the pin jacking was established on the face of the press bolt edge of the block. This was accomplished by a slow increase of the pin stroke as the result of an increase of the hydraulic pressure using the hydraulic hand pump.

Figures 5a and 5b show a simplified scheme of the head deformation measurement concept. A scheme simplification consists of two elements: first is omitting a press bolt drawing (as the bolt is required only to provide a full contact with the pin face and to prevent plastic deformations in the body of the block which would be done during jacking of the pin). A second simplification element is to depict phenomena related to a deformation of certain head elements, including a head cap as well as a pin-piston-slider-coil core assembly, as a generalised jack head deformation value l_H.

After reaching the contact of the pin and the face of the press bolt, a recording cycle of parameter readouts was started in the SBP View software. Then, a cycle of increasing the pressure up to a maximum operating value was performed. The recording of the parameter values was stopped after reaching the maximum hydraulic pressure value. An each measuring cycle provided up to 6000 readout sets of the measured parameters in the computer's memory.

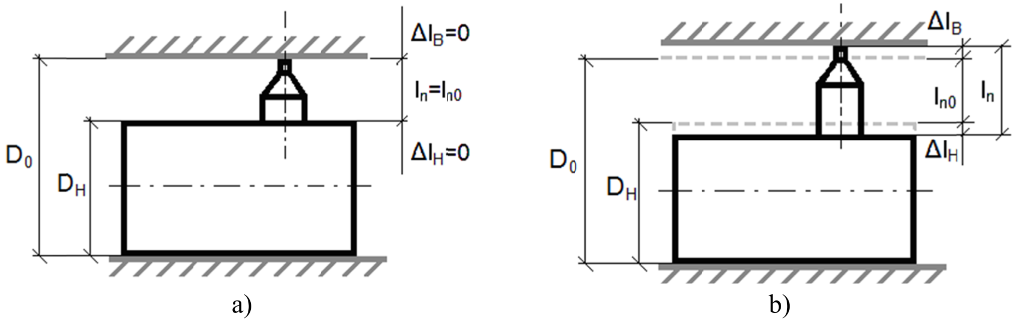


Fig. 5. The simplified concept diagram of the bench test measurement parameters: a) initiial measurements, b) test cycle measurements. l_n – pin stroke measurement taken by a pin stroke transducer in the jack head, Δl_B – measurement block deformation measured by an external transducer, jack head deformation Δl_H. a) the proper measurement starting point (pin jacking), b) measurement phase (during increase of the pressure)

3.2.3. An analysis of the bench test results

An analysis of the measurement results (p_n, l_n, l_B) started from the point defining the pin properly prepared to jack against the block internal opening's walls. Therefore, for the each recorded set of readout values, initial measurement values were determined:

1. p_{n0} – a pressure needed to move out the pin from the head to the point it is prepared to jack against the face of the press bolt [MPa],
2. l_{n0} – the stroke of a pin prepared to jack against the block [mm],
3. l_{B0} – an initial measurement block height [mm].

Then, following parameter values were determined for each subsequent time interval (5 ms) of the measurement cycle:

1. the hydraulic pressure increase, Δp_n [MPa],

$$\Delta p_n = p_n - p_{n0} \tag{14}$$

2. the pin stroke increase, Δl_n [mm],

$$\Delta l_n = l_n - l_{n0} \tag{15}$$

3. a block height change, Δl_B [mm],

$$\Delta l_B = -(l_B - l_{B0}) = l_{B0} - l_B \tag{16}$$

4. a head deformation, Δl_H [mm],

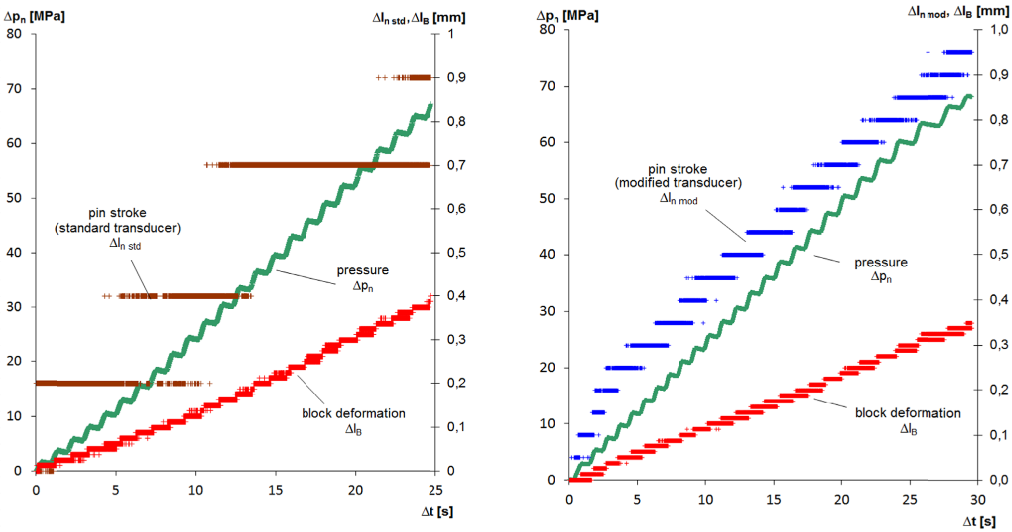
$$\Delta l_H = \Delta l_n - \Delta l_B = l_n - l_{n0} - (l_{B0} - l_B) \tag{17}$$

A first stage of the bench test result analysis consisted of examining first three aforementioned parameters characteristics as a function of time.

Figures 6a and 6b show the results of test measurements for two heads, one equipped with a standard pin stroke transducer, and the other with a modified one. The charts show increase of the hydraulic pressure, the pin stroke increase and the block height change.

It can be assumed that an average hydraulic pressure growth rate was generally constant for each of the measurements, and it reached approx. 2.7 MPa/s (Fig. 6a) and 2.3 MPa/s (Fig. 6b). Hydraulic pressure growth rate depended on a skill of a person operating the hydraulic hand pump.

Based on the obtained pressure readouts in the bench test a conclusion was drawn that increasing the standard 0.1 MPa pressure measurement resolution of the analogue-to-digital converter of the borehole jack control panel up to 0.05 MPa has no significant impact on the quality of pressure measurements. Instead, a closer attention should be put on improving the resolution of the pin stroke measurement.



a) b)

Fig. 6. Charts of the bench tests for: a) the standard pin stroke sensor transducer,
b) the modified pin stroke sensor transducer

The measurement results demonstrated that for a maximum pressure of $\Delta p_{n\ \max} = 68.2$ MPa obtained in the hydraulic system, a maximum block deformation measured by the external transducer was about 0.36 to 0.40 mm, whereas a maximum pin stroke measured by the standard and modified transducers reached maximum values of about 1.0 mm.

The individual transducer resolutions provided a range of the measured values in a following numbers of discrete value levels:

- for the pressure increase Δp_n – approx. 1360 discrete value levels with a MADC-06 converter resolution of 0.05 MPa and a measured value range of 0-68.2 MPa,
- for the block height change Δl_B – 32 discrete value levels with the external transducer resolution of 0.0125 mm and a measured value range of 0-0.4000 mm.

Meanwhile, the readouts of the pin stroke increase Δl_n, of the standard pin stroke transducer with a theoretical resolution of up to 0.1 mm provided only 5 discrete value levels up to 0.9 mm, whereas the modified pin stroke transducer with the resolution of 0.05 mm provided 20 discrete value levels up to 0.95 mm.

In the chart showed in Fig. 6a, it can be observed that increments between each discrete values of standard transducer (brown series) demonstrate that this transducer is characterised by a non-linear resolution. Furthermore, the five observed discrete values of this transducer's readouts are much less than recommended by the ISRM for producing a reliable deformation characteristic. This conclusion proved that the modification of a pin stroke readouts was really needed.

The determined parameters Δp_n, Δl_n and Δl_B were presented graphically (Figs. 7a and 7b) as:

– $\Delta l_{n\ std} = f(\Delta p_n)$: a characteristic of the pin stroke increase readouts of the standard pin stroke transducer as a function of the pressure increase – brown series (Fig. 7a),
– $\Delta l_{n\ mod} = f(\Delta p_n)$ a characteristic of the pin stroke increase readouts of the modified pin stroke transducer as a function of the pressure increase – blue series (Fig. 7b),
– a reference characteristic (a block deformation): $\Delta l_B = f(\Delta p_n)$ – the measurement block height change as a function of the pressure increase – green series (Figs. 7a and 7b).

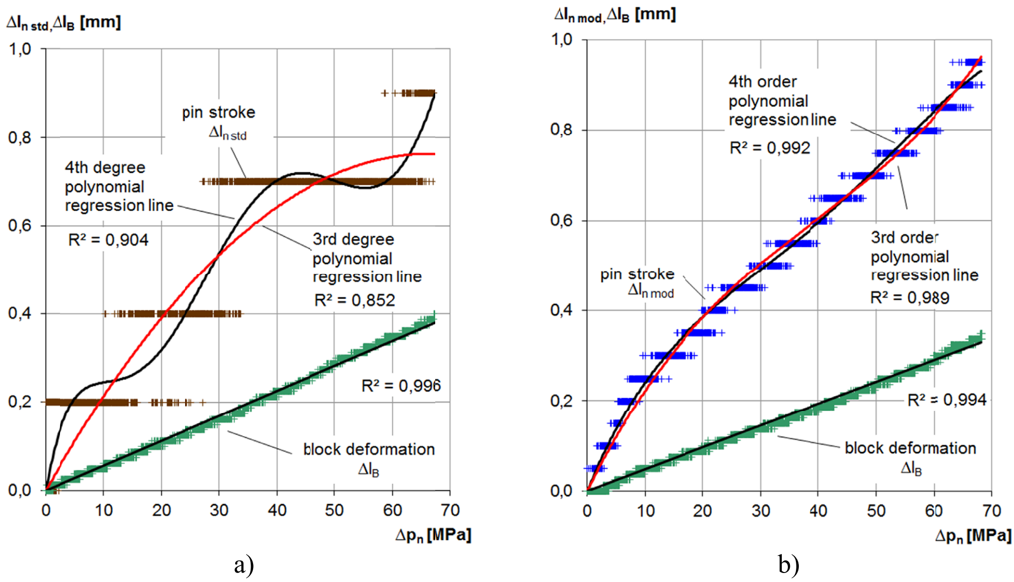


Fig. 7. Pin stroke transducer measurements and real pin stroke as functions of pressure growth, measured in: a) head with standard pin stroke transducer; b) head with modified pin stroke transducer

The bench test results analysis confirmed the assumption that the pin stroke increase results measured by the pin stroke transducer could be greater than the real pin face position determined by the block height change measurement. In fact, the real pin displacement was less than 40% of the maximum pin stroke readout.

In other words, the deformability of the jack head has a significant influence on the pin stroke readouts. This notice was the same for the both tested transducers (a standard and modified one). Possible reasons for this observation may lie in factors such as structural clearances between cover head body and other head parts or a non-linear displacement of the coil's core, relative to the displacement of the piston in the head.

The scope of the Central Mining Institute's first stage of the statutory work related to the suitability assessment of the Pen206 borehole jack allowed to obtain a preliminary empirical description of the modified pin stroke correction characteristic. For this purpose, the characteristics of the standard pin stroke transducer and the modified one as well as the change of the measurement bock height were subjected to a preliminary regression analysis.

A purpose of the regression analysis was to find and fit an empirical function that would describe the measurement characteristic in an optimum and realistic way. The characteristic should reflect the mechanical properties of the borehole jack head, especially considering stiffness of the head parts and structural clearances between them.

For the preliminary regression analysis purpose, a polynomial regressions of 1st to 6th order with constant coefficient $a_0 = 0$ have been chosen. Such a regression analysis type, based on the Weierstrass theorem [Polanowski, 2004] should have a capability of approximating a whole obtained data set with a one equation, easy to implement for the correction of the borehole jack test measurement readouts.

Obtained trend lines of of 1st to 6th order polynomial regression underwent graphical analysis. However, it was observed that increase of the polynomial regression order above certain level, could increase the risk of overfitting, which is manifested as a loss of the trend generalisation ability. That means it fits too strictly to the analysed data set. This overfitting can be manifested by an unrealistic curvature of the trend line in the upper data range. An another risk of choosing too high polynomial regression order is the occurrence of Runge's phenomenon (trend line oscillations between equidistant polynomial interpolation nodes), which results in the generation of local regression trend line convexity variations that disrupt the linearity of the trend.

Considering the necessity to compromise between underfitting and overfitting of the regression analysis, the authors believe it to be more beneficial to utilise polynomial of no lower than preferably the 4th order, due to the more accurate approximation of the pin stroke readout correction in the lower measuring range, i.e. for pressures up to approx. 20 MPa. This fact is significant from the perspective of conducting borehole jack measurements in weak rock strata characterised by low uniaxial compressive strength (UCS) values up to a value of 20 MPa. This range of rock mass UCS is often characteristic of the Cracow sandstone series (Westphalian C and D) at the eastern edge of the Upper Silesian Coal Basin.

The measurement block deformation (the height change) characteristic $\Delta l_B = f(\Delta p_n)$ can be considered linear along the entire measuring range; for the maximum pressure increase of approx. 68.2 MPa, the maximum block deformation $\Delta l_{B\,\max}$ was less than 0.4 mm forth both heads.

The $\Delta l_B = f(\Delta p_n)$ form of this characteristic presentation is similar to the well-known mechanical stiffness characteristic type $F = f(l)$, due to the possibility of easy expressing of the pressure increase Δp_n with a force increase ΔF_n while knowing the surface areas of the piston and the coil's core in the borehole jack head from following equation:

$$\Delta F_n = \Delta p_n \cdot \left(0{,}25 \cdot \pi \cdot (d_p^{\,2} + d_c^{\,2})\right) \tag{18}$$

with:

$d_p = 0.02$ m — a diameter of the piston of the borehole jack head,
$d_c = 0.005$ m — a diameter of the coil's core.

So, the maximum force increase was of 22.76 kN.

A mechanical stiffness k of the body could be determined as

$$k = dF \,/\, dl = \Delta F_{n\,\max} \,/\, \Delta l_{B\,\max} \tag{19}$$

For the maximum obtained change of the block height for the bench test involving the modified pin stroke transducer measurements $\Delta l_{B\ \mathrm{max}} = 0.36$ mm, the stiffness of the measuring block k_B was calculated as of 63.24 kN/mm

Based on the bench test result analysis obtained with the standard pin stroke transducer (Fig. 7a), the conclusion was drawn that it is impossible to reasonably select an approximation function for this type of transducer that would reflect in effect a real characteristic of the head deformation. To illustrate efforts made to find this function, the 3rd and 4th order polynomial curves are depicted in Fig. 7a (blue and black curves). The employed polynomial curves constitute examples of underfitting and overfitting of trend lines to the measurement readouts. The low and non-linear resolution of the original transducer didn't offer reliable measurement readouts and, consequently, it wasn't possible to obtain a high degree of fit for any of the analysed 2$^{\mathrm{nd}}$ to 6$^{\mathrm{th}}$ order polynomials to the measurement results, regardless of rather high R^2 coefficient values.

The regression analysis of the bench test results for the modified pin stroke transducer (Fig. 7b) demonstrated the possibility of using a polynomial regression function with a very high degree of fit. The R^2 coefficient had values at least 0.99 for 3rd and 4th order polynomials.

However, Fig. 7b shows again a significant difference between the pin stroke measurement results done by pin stroke transducer and the result of its measurements by external transducer.

The measurement results show that it is necessary to apply an empirical correction to the modified pin stroke transducer measurement results in order to obtain the real pin stroke value.

A second stage of the bench test result analysis was to obtain a modified pin stroke transducer readout correction characteristic $\Delta l_H = f(\Delta p_n)$ (Fig. 8). The results of measurements done by the modified pin stroke transducer needed to be adjusted relative to the results of measurements of the real pin stroke, according to the following formula:

$$l_H(\Delta p_n) = \Delta l_n(\Delta p_n) - \Delta l_B(\Delta p_n) \tag{20}$$

The modified pin stroke transducer readout correction characteristic $\Delta l_H = f(\Delta p_n)$ (Fig. 8) can be defined by two distinct segments. The characteristic initially has a curvilinear segment up to a pressure of ca. 20 MPa that may represent a phase of elimination of structural clearances between individual head parts. For the pressure higher than 20 MPa the characteristic takes a linear form, which is typical for a linear-elastic body.

Defining a boundary between the two aforementioned segments of the stiffness characteristic may be in practice difficult and is dependent on the order of the used polynomial regression function. It is advisable rather first to limit or eliminate structural clearances in the borehole jack head assembly by appropriate modifications in the design of the head.

Figure 9 shows a readout correction characteristic of the modified pin stroke transducer in the four possible unit forms of the following basic relationship: $\Delta p_n = f(\Delta l_H)$.

The head deformability could be expressed as the strain ε_H of the head equivalent material body from following equation:

$$\varepsilon_H = \Delta l_H / (D_H + l_{n0}) \tag{21}$$

with:

$D_H = 85.0$ mm — borehole jack diameter,
$l_{n0} = 2.1$ mm — stroke of pin prepared to jack against the block, during the bench test.

During searching for a linear segment of the pin stroke transducer readout correction characteristic, a trend line of a selected 4th order polynomial for the regression analysis was analysed

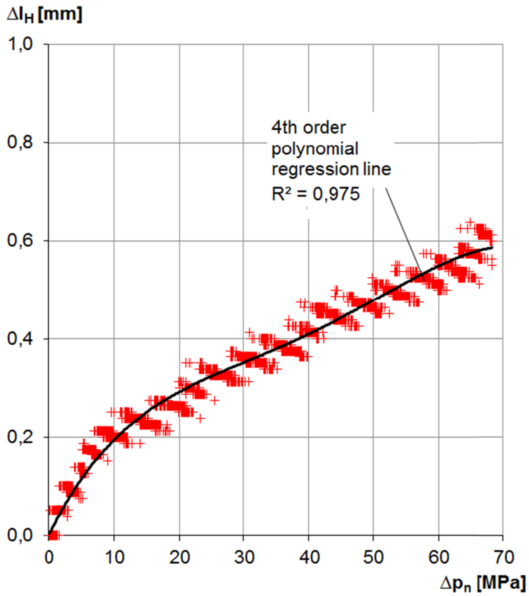


Fig. 8. Correction characteristic of the modified pin stroke transducer readout (expressed as a relationship between measured parameters: Δl_H and Δp_n)

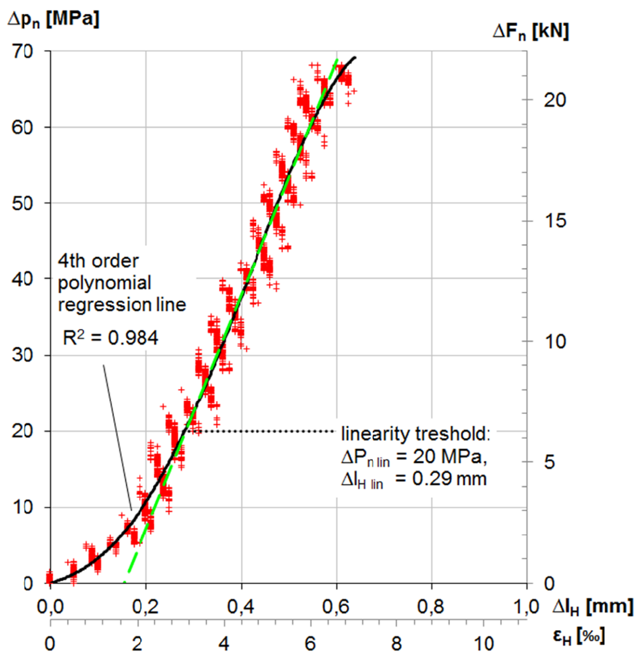


Fig. 9. Correction characteristic of the modified pin stroke transducer readout (expressed as a relationship between Δp_n or ΔF_n and Δl_H or ε_H)

using a graphical method, which determined the segment of linearity of the polynomial trend line for a pressure in the hydraulic system from the range of approx. 20 to 60 MPa and the head deformation Δl_H (the pin stroke readout correction) equal to or greater than approx. 0.29 mm. However, it can be observed that for maximum pressure values (approx. 60 to 68 MPa) the polynomial trend line shape differs from the interpolated straight trend line. This is most likely a result of overfitting the 4th order polynomial trend line to the data set, which has a characteristic "step-like" shape resulting from the discrete parameter readout values and different measuring resolutions of the measurement block deformation transducer and the pin stroke transducer. However, bypassing of this problem could be accomplished, for example by utilising a cubic spline regression or by limiting the practical readout correction range to a pressure range of up to 60 MPa, which is anyway practised in standard Pen206 borehole jack *in situ* measurements as a hydraulic pump's operational safety limit.

Based on the calculations done on the linear trend line of the correction characteristic fitted to the range of proportional pressure/deformation increase above point of 20 MPa / 0.29 mm, a head mechanical stiffness k could be determined as k = 48,3 kN/mm. Should the clearances within the borehole jack be theoretically eliminated, the corrected (reduced) pin stroke $\Delta l_{n\,red}$ would be an equation of:

$$\Delta l_{n\,red}(\Delta p_n) = \Delta l_n - \Delta p_n / k, \text{ for } \Delta p_n = 0 \text{ to } 60 \text{ MPa} \tag{22}$$

In practice, this equation is limited to the range of measured pressure increase no less than 20 MPa, so the equation should be:

$$\Delta l_{n\,red}(\Delta p_n) = \Delta l_n - 0.29 \text{ mm} - (\Delta p_n - 20 \text{ MPa}) / k, \text{ for } \Delta p_n \geq 20 \text{ MPa} \tag{23}$$

At last, the general form of such equation, for $\Delta p_n \leq 60$ MPa (upper limit of borehole jack pressure measurements), using 4th order polynomial, should be:

$$\begin{aligned}\Delta l_{n\,red}(\Delta p_n) = &-9{,}5 \cdot 10^{-9} \cdot \Delta p_n^{\,4} + 1545 \cdot 10^{-9} \cdot \Delta p_n^{\,3} + \\ &- 87868 \cdot 10^{-9} \cdot \Delta p_n^{\,2} + 2671092 \cdot 10^{-9} \cdot \Delta p_n\end{aligned} \tag{24}$$

The lower extrapolation of the trend line of the linear jack head stiffness characteristic also shows that the theoretical sum of structural clearances between head parts should be of approximate 0.15 mm. This conclusion should be experimentally verified.

3.3. The assessment of the borehole jack parameter measurements recording capability

Based on the analysis of the test results and the hardware specification of the control panel of the borehole jack (parameters of built-in analogue-to digital converter, an amount of data from each measurement cycle, a data recording rate, an available memory capacity) a an initial conclusion was drawn that the jack control panel has the hardware specification capable of measuring simultaneously the pin stroke and the hydraulic pressure. Given the compromise between a digital memory storage capacity and a total amount of measurement cycles, it was decided initially to set a readout rate of 50 cycles per second. The available amount of measurements has been divided to a set of 5 boreholes of a length of 10 m with a possible depth increase of 0.1 m between each measurement cycle.

4. Conclusions

The suitability assessment of the Pen206 borehole jack was divided into two groups of conclusions. A first group depicted a current state of the assessment, based on hardware modifications, tests and analyses of the measurement results, performed so far within the scope of the Central Mining Institute's statutory work no. 11122028:

1. The standard 0.1 MPa pressure measuring resolution of the analogue-to-digital converter of the borehole jack control panel should be sufficient enough for the pressure measurement purpose.
2. The analysis of the results of the bench tests confirmed the assumption that the measuring resolution and accuracy of the standard pin stroke transducer CZP v0.1 aren't acceptable. Thus, the improvement of the borehole jack pin stroke measuring properties by implementing the modified pin stroke transducer CZP v0.2 was a right solution.
3. The bench test results also confirmed that the mechanical properties of the borehole jack head (its deformability) alter the values of the measured pin stroke readouts and should be adjusted using the pin stroke readout correction characteristic.
4. An each jack head specimen has its own unique deformability characteristic that should be determined by performing the bench test and appropriately implemented during the analysis of the results of a field borehole jack test cycle.
5. In the current state of the borehole jack head analysis, a preliminary solution of obtaining the pin stroke readout correction characteristic was to use the data obtained from the bench test. The correction characteristic could be depicted as an empirical relationship between the pressure increase and the jack head deformation in the form of a polynomial function of the 4th order.
6. The correction characteristic of the modified pin stroke transducer readout data exhibited a non-linear behaviour over a hydraulic pressure range of up to approx. 20 MPa. This non-linearity could be a result of a phase of progressive reduction of structural clearances between individual head elements during jacking and it may be possible to reduce or even eliminate in the future by redesigning of some of the head parts.
7. The jack control panel has the hardware specification capable of measuring simultaneously the pin stroke and the hydraulic pressure. Given the compromise between a digital memory capacity and a total number of measurement cycles, it was decided initially to set a readout rate of 50 cycles per second.
8. Based on aforementioned conclusions, the final observation is that there is a possibility to measure the deformability of rock mass in the HQ boreholes by using the modified Pen206 borehole jack.

The second group of conclusions shows directions for a future development and modifications of the borehole jack:

9. The modified pin stroke transducer's resolution allows for the future determination of the jack performance characteristic. This characteristic is a correlation between the free pin stroke and the hydraulic pressure. The performance characteristic is essential to adjust the hydraulic pressure readouts.
10. After the elimination or reduction of structural clearances, additional tests should be performed to check the linearity of the kinematics between the piston and the modified pin stroke transducer's core as the function of the hydraulic pressure during the jacking cycle.

11. As the pressure transducer is located in a different place than a modified pin stroke transducer (i.e. in the hydraulic pump's assembly), a concurrence between the pressure and pin stroke readouts also should be determined and corrected in a test involving a dynamic movement of the pin, as it occurs in a very moment of the rock structure destruction.
12. A precise pin stroke readout correction characteristic could be determined for a jack head with (hopefully) eliminated structural clearances, based on the concurrent pressure and pin stroke readouts, using a potential pin stroke linearity adjustment and the determined jack performance characteristic.
13. To verify the aforementioned directions of measurement improvements, the head should undergo further experimental testing, potentially supported by a numerical modeling simulation.
14. An additional test could be performed to check a dynamic properties of the borehole jack's measurement equipment – it means what fastest increment of the pressure and the pin stroke could be recorded. A practical use of a such test is knowledge if the measuring equipment is able to record the detailed parameters of the very moment of the rock structure destruction.
15. Further tests conducted with the modified borehole jack should involve the measurements in boreholes drilled in a material characterised by mechanical properties similar to a typical rock mass, preferably under a stress field range similar to that in the hard coal mine. Results of a such tests could be then compared to the geomechanical rock mass properties determined by another acknowledged method in order to find empirical relations between these types of methods.

5. Summary of the current state of the suitability assessment

So far, there was no suitable method of the determining weak rock mass deformability parameters to use in the Polish hard coal mines. Available methods (laboratory triaxial testing) or various field methods have some disadvantages which prevent from using them on a larger scale. The only frequently used field method of some of the geomechanical parameters is the borehole jack rock mass strength test.

As the borehole jack rock mass strength test and some other static methods of rock mass deformability determination do share a common principle of operation, an idea was raised to expand the metrological capabilities of the Pen206 type borehole jack, which is a well-known tool used to examine rock mass properties in the Polish hard coal mines.

To properly assess the suitability of the Pen206 borehole jack on the rock mass deformability determination purpose, a few questions had to be answered first:

– a prospective range of a borehole wall surface deformability to be measured,
– a minimum required resolution and precision for reliable rock mass deformability measurements,
– a possible alteration of an equipment properties on measurement readouts,
– a direction of future modifications of the existing equipment, preferably without breaching a current borehole jack ATEX certificate.

This paper includes basic answers for the aforementioned questions, provided by the completion of the Central Mining Institute's statutory work no. 11122028.

The implemented Pen206 borehole jack modifications to the pin stroke measuring system and the data recording system, combined with the analysis of the bench test results showed that it is possible to use the Pen206 borehole jack for the purpose of determination of deformation parameters of rock mass. However, during current stage of the assessment process, new issues were raised, which require further development and testing of the borehole jack. Conclusions in this paper also show directions of future research on improving deformability and strength parameters measurements.

The standard borehole jack method is used for over forty years in Polish hard coal mines to determine some of the rock mass strength parameters. Authors of this article hope that after completion of the designated modifications and tests, the modified Pen206 borehole jack method could be also an interesting alternative to other field methods of determining rock mass deformation parameters. The modified borehole jack method has some relevant advantages as the simultaneous rock strength and deformability testing, equipment portability, a quick performance of measurement cycles in any desired depth or orientation of the jack head within the borehole space. It is conceivable that a successful completion of each proposed modifications or tests could open a new perspective of further development of the current equipment or create a new field of use of the borehole jack. Also, authors hope that experience gained as a result of this work could be an important contribution in designing a new generation of the borehole jack designed for measurements in boreholes of a smaller diameter than HQ size.

Acknowledgments

This article was written as a part of the accomplishment of Central Mining Institute's statutory work no. 11122028, financed by the Ministry of Science and Higher Education.

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