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SECOND GENERATION OF CONICAL STRAIN GAUGE PROBE FOR STRESS MEASUREMENT IN ROCK MASSIF

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ABSTRACT
Compact conical strain gauge probe for borehole over-coring rock massif stress measurement (CCBO), based on experiences of K. Sugavara and Y. Obara, has been developed in Institute of Geonics ASCR, v.v.i. from 2004. First generation of CCBO is equipped by simple electronic circuit which requires continuous communication with control computer in the course of measurement. Prototypes of this type probes are used for long term stress changes monitoring induced by longwall advancement in mine. Solving of continuous data communication through rotating drilling tool filled by wash water in course of over-coring is very difficult technical task, which is not possible to solve in terms of grant project. To avoid this problem a development of second generation of CCBO equipped by microprocessor and internal data logger was initialised. Simplified modification of CCBO is developed as a probe for long-term monitoring of rock massif stress changes (Compact Conical Ended Borehole Monitoring - CCBM). Design of both models probes, discussion of measurement errors and technique of sensitivity self-calibration is described.

KEYWORDS: stress measurement, over-coring

INTRODUCTION

The questions of rock stress and its measurement has been investigated in Institute of Geonics of ASCR (IG) for a long time. Hydrofracturing is usually used for stress measurement in our Institute. This method does not make possible to measure total stress tensor. That is why we decided to develop a device making the determination of the total state of stress tensor possible. Development of this device was based on experiences of prof. K. Sugawara and prof. Y. Obara from Kumamoto University, who have been using the compact conical ended borehole over-coring system (CCBO) for the first time (Nakamura et al, 1999; Kang, 2000). Conical shape of the strain gauge head CCBO makes the fixation of the probe in borehole easy and makes the measurement of stress in independent directions possible. Using of conical shape of measuring surface brings together both advantage of determination of total stress tensor in one position and advantage of simple installation and centering of the probe in borehole. Relatively short compact segment of rock is required for application of over-coring method in this case.

We could not apply Obara's instrumentation and methodology of over-coring rock massif stress measurement without modification due to different construction of drilling machines in Czech Republic. Japan drilling machines have straight-through hole in carrier of drilling tool, therefore it is possible to realize wire connection between CCBO probe and classic strain-gauge measuring bridge in the course of over-coring. That is why Japan CCBO probe is very simple because it only contains 8 strain gauges 2-element 90˚ tee-rosettes – see Fig. 1.

Fig. 1 Design of Japan CCBO probe.

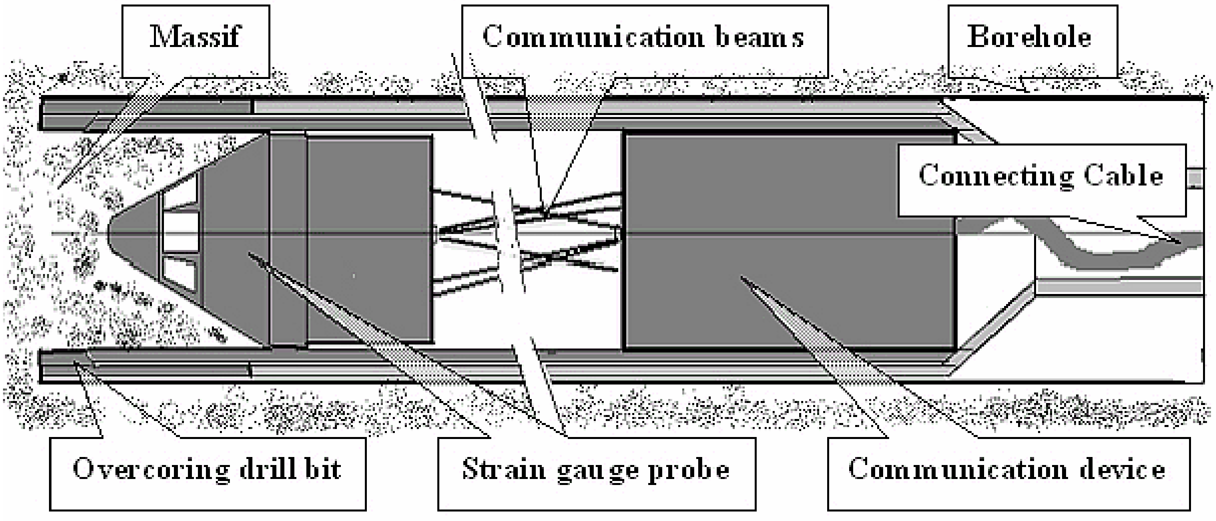

Fig. 2 Conception of disposition of 1st generation CCBO equipment in borehole (Staš et al., 2005a).

Unfortunately, the carriers on drilling machines used in Czech Republic are impassable; therefore it was necessary to solve some methodology for deformations measurement and data recording directly inside rotating drilling tool.

First generation of our CCBO instrumentation was based on optical infrared serial communication between CCBO probe glued in the bottom of borehole and rotating communication device connected to data-logger installed in rotating drilling tool - see Fig. 2.

Basic theory of CCBO over-coring methodology, design concept of our 1st generation CCBO instrumentation and reached results are described in papers Staš et al. (2005a, 2005b, 2007a, 2007b).

Serial data output of 1st generation probe enabled us to develop simplified modification of CCBO for long-term monitoring of rock massif stress changes (Compact Conical Ended Borehole Monitoring - CCBM). The 1st generation CCBM probe communicates with data-logger through standard serial port COM (standard RS-232, 4800 bps, 8 bit, no parity). Results of investigation of rock massif stress changes induced by longwall advance on Lazy Colliery (Ostrava-Karvina Coal Basin) are described in paper Staš et al. (2007b).

The most difficult, for scientific institute practically unsolvable problem, was solution of reliable digital data transmission from CCBO probe to data-logger in course of over-coring through rotating drilling tool in water media. That is why conception of 1st generation CCBO probes has been left and we begun development of 2nd generation of CCBO probe equipped by built-in microprocessor based data-logger which enables:

- Data logging in course of over-coring without requirement of communication with external equipment.
- Decreasing of data scattering using digital processing of measured values (averaging).
- Using of failsafe (CRC protected) protocol for operation control and data transmission which enables reliable long distance communication.
- Integration of CCBM probe as an intelligent addressed remote sensor to distributed data acquisition systems.
- Operation of CCBM probe in mode compatible with 1st generation CCBM.

CONCEPT DESIGN OF 2nd GENERATION CCBO PROBE

Simplified block diagram of 2nd generation CCBO probe is presented in Figure 3. Probe consists of two principal separable parts:

- Measuring conical tip containing 6 strain gauge 2-element 90˚ tee-rosettes (longitudinal: T1L-T6L and transversal: T1T-T6T) and alkaline battery B 6.4 V.
- Body of probe containing electronic multiplexed quarter strain gauge bridge MUX, analog-to-digital converter A/D, microprocessor MP, EEPROM data memory, stabilized power supply, TTL/RS-232 interface, serial input/output connector CAN 9M and clock-calendar chip (optional).

Body and conical tip are interconnected by pair of 26-pin connectors (CAN 26F, CAN 26M). Connector CAN 9M is being done for serial communication with control computer and insertion of external power. Body is reusable. After finish of over-coring experiment it is possible to cut CCBO probe in plane of separation and install new conical tip. All

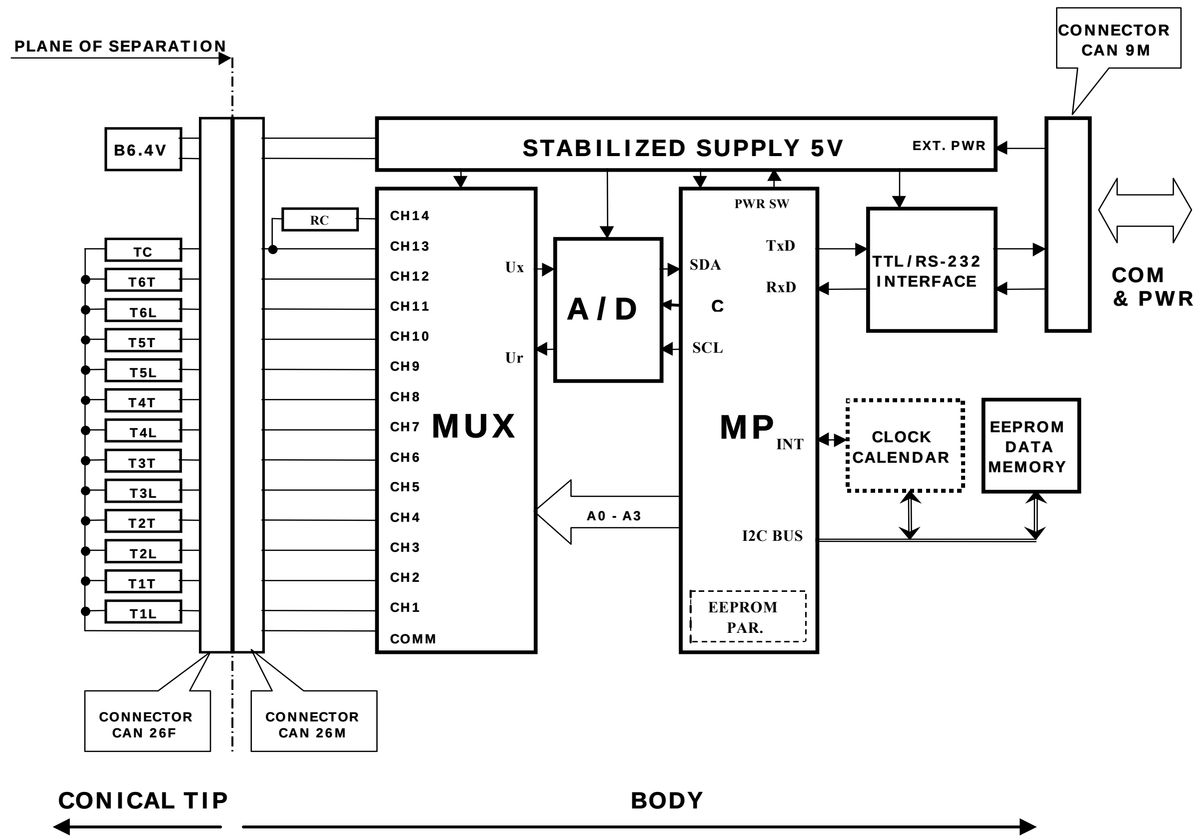

Fig. 3 Simplified block diagram of 2nd generation CCBO probe.

circuits inside body are powered through stabilized supply 5V (SP) from two possible power sources:

- External power source (EXT.PWR) conducted by connector COM&PWR during tests of probe and setting-up of experiment parameters.
- Internal battery B 6.4V inside conical tip conducted by connector CAN26 during over-coring experiment.

Microprocessor MP controls the functions of all other circuits. MP contains internal memory EEPROM PAR in which parameters for probe identification and control parameters of experiment are stored. MUX is controlled by address signals A0-A3. A/D and MUX have common source of reference voltage Ur. 16-bit A/D is connected to MP serially (SDA, SCL). A/D conversion of measured voltage Ux is started by command C (convert). SZ is possible to switch off by signal PWR SW = 0 after finish of over-coring measurement.

EEPROM DATA MEMORY is connected with MP via internal I2C bus. The CLOCK CALENDAR chip is not used now (Free position is prepared in PCB layout). TTL/RS-232 interface converts TTL signals (RxD, TxD) of UART of MP to RS-232 voltage levels.

Key issue of construction of CCBO is to achieve a sufficient stability of balance and low noise level of the being non-contact multiplexed DC supplied strain gauge quarter bridge. The resistances of semiconductor switches in switched state (RS), about 50Ω, are comparable with the resistances 350Ω of used strain gauges. For this reason an electronic circuit that eliminates RS was developed – see Fig. 4.

There are measuring strain gauges T1L...T6T (in Figure 4 represented by T1L), compensanting strain gauge TC, calibration resitor RC and semiconductor switches in a form of ideal switches S1a...S14b and their substitutive resistances RS1a...RS14b. The compensanting strain-gauge TC is assembled inside conical tip, therefore it is not strained. Switching is controlled by binary address A0...A3 via address decoder which perform switching of corresponding pairs of switches, for example S1a and S1b in Figure 4. In reality MUX has 16 channels (CH0 – offset of amplifiers, CH15 – measurement of B 6.4V voltage).

Resistors R1, R2, R3 and corresponding strain gauge with operational amplifier OZ_C create

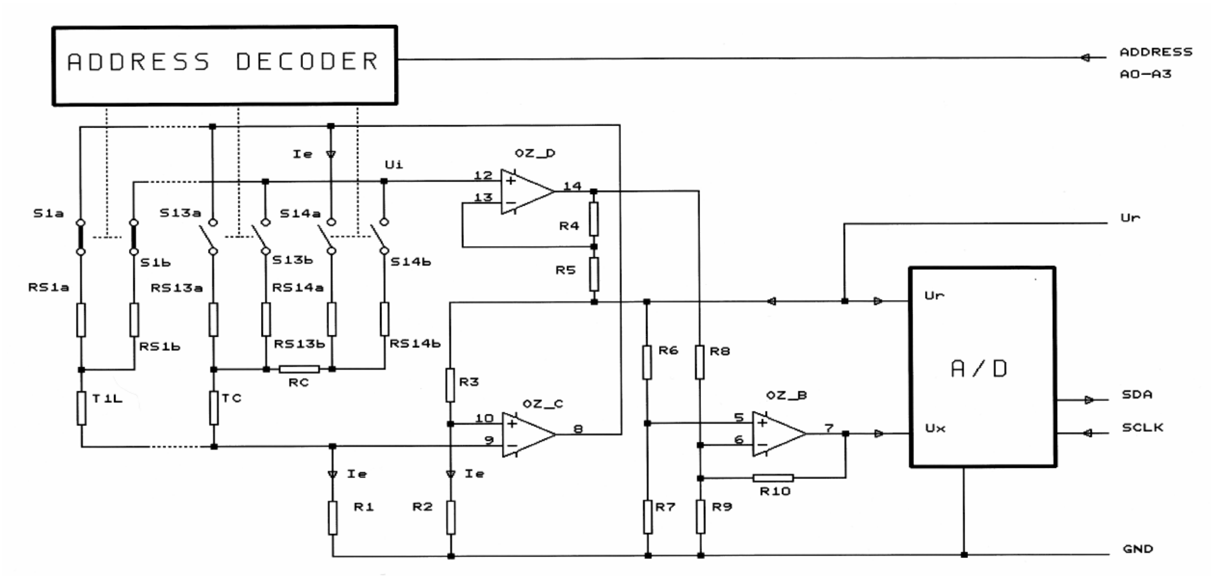

Fig. 4 Principal circuit diagram of multiplexed strain-gauge quarter bridge (MUX).

linearized full bridge. The resistance of strain gauge connected to channel CH is defined as $RT[CH] = R0[CH].(1 + k.x)$, where R0[CH] is resistance of addressed strain-gauge without strain, k is gage factor (we assume the same k for all strain gauges) and x = Δl/l is strain. The operational amplifier OZ_C holds zero voltage between its inputs by the influence of negative feedback. Voltage on the non-inverting input of OZ_C is constant (derived from Ur) and R1 = R2 (P1), therefore output of OZ_C supplies strain gauge with constant excitation current Ie. The bridge is linearized. Signal from strain-gauge T1L is taken to non-inverting input of OZ_D via RS1b and S1b. Resistances RS1a and RS1b have no influence. If R0 = R3 (P2) bridge is balanced and Ui = Ur. By conditions R6 = R7 and R8 = R9 (P3) useful signal, proportional to stress, is defined Ux[adr] = Ur.(0.5 + R0[adr].k.A.x/(R2+R3)), where A is voltage amplification of OZ_C and OZ_C.

$$Xm[CH] = 2^{14}.(Ux[CH] - 0.5.Ur)/Ur.$$

After substitution:

$$Xm[CH] = 2^{14}.R0[CH].k.A.x/(R2+R3) = C.x,$$

where C is resulting constant of sensitivity. It is evident, that value Xm[CH] is independent on Ur but depends on values of all resistors in circuit. Dynamic range of analog circuits is about +/- 5000 μStrain. With 16-bit A/D in bipolar regime we obtain resolution 0.3 μStrain/LSB.

Due to DC regime of measurement, low excitation current Ie and fast charge redistribution SAR type of A/D conversion there is indispensable noise subtracted to measured values of strain. To suppress the noise, averaging of n_avg results of measurement is used (default n_avg = 64). Averaged values are marked by suffix avg (e.g. X[CH]avg). By averaging of n_avg values the noise will decrease approximately √n_avg times (default 8 times).

MP inside contains internal EEPROM in which parameters for probe identification and measurement control are stored. External EEPROM data memory (EEPROM DATA MEMORY) connected on I2C bus is installed to CCBO probes only. Clock-calendar chip is not used at present, position for it is prepared on PCB layout. Interface TTL/RS-232 converts signal levels between MP UART and RS-232 COM port.

CORRECTION OF BRIDGE UNBALANCE AND CALIBRATION OF SENSITIVITY

In practice it is impossible to fulfill ideal balance of bridge (conditions P1, P2, P3) because of limited precision and stability of resistors used. Used strain-gauges show the temperature dependence aboutn5 μStrain/K. Operation amplifiers have temperature dependent offset of input voltage and current, too. Above-mentioned influences will be shown as systematic common temperature dependent bridge unbalance ΔX0(t), the same for each strain gauges.

By influence of production tolerances of strain-gauges individual R0[CH] are not equal. Different parasitic mechanical stresses arising at process of hardening of casting compound and sticking the probe on in the borehole. As a result, individual errors of balance ΔX[CH] occur. Measured averaged value is given as a sum:

$$Xm[CH]avg = \sum_{1}^{n\_avg} (\Delta X0(t) + \Delta X[CH] + X[CH]) / n\_avg$$

Above mentioned errors is possible to eliminate numerically in the process of data interpretation. Compensating strain-gauge is connected to CH13. Measured averaged value Xm[13]avg carries information about ΔX0(t) predominantly, because ΔX[13] is set near to zero during process of manufacturing of conical tip and X[13] = 0 (TC is not stressed). When Xm[13]avg is subtracted from Xm[CH]avg temperature dependence of bridge unbalance ΔX0(t) is eliminated:

$$Xm[CH]avg - Xm[13]avg = \sum_{1}^{n\_avg} (\Delta X[CH] - \Delta X[13] + X[CH]) / n\_avg$$

If we have stored initial value measured after installation of probe and/or on the beginning of over-coring, it is possible subtract it from measured values and obtain proper values of X[CH]avg.

Calibration resistor RC is connected in series to TC. On the basis of parameter calibration stored in EEPROM PAR and measured value of CH[14] it is possible to calculate correction constant of sensitivity for other channels.

Interpretation program is equipped by special function for automatic correction of sensitivity based on matching of calibration constant stored in EEPROM PAR. and Xm[14]avg channel in measured data.

MODES OF CCBO PROBE OPERATION

There are 2 principal modes of CCBO probe operation:

- Slave mode for laboratory testing, installation in borehole and setting-up of over-coring experiment parameters (range of data memory, sampling period and internal battery power source switch-on).
- Autonomous mode for over-coring experiment.

In the slave mode CCBO probe is connected by cable with the control computer (master unit) and external power source. Communication protocol AIBus-2 (www.tedia.cz) is used for fail-safe command and data transmission. This protocol is used due to implementation of probes to the distributed control and measuring system in Jeroným Mine – see Knejzlík and Rambouský (2008). In slave mode full control of probe operation is possible (setting-up of parameters, start and stop of measurement, data memory erasing etc.).

After switching-on of internal battery power source and start of measured data recording to the DATA MEMORY CCBO comes to autonomous mode. The communication cable is possible to wrest from COM&PWR connector.

Measurement is triggered in autonomous mode by internal counter. Function is optically indicated by glimmer (period 1s) of check LED diode (see Fig. 5). Packets of 32 byte (no fail-safe straight binary code, 2 byte per channel) of measured data are transmitted via COM port for purposes of functional test. After achievement of default maximum address of data memory internal power source of CCBO is switched off.

DESIGN OF CCBO PROBE

Mechanic design of CCBO probe is shown in Figure 5. The probe consists of two parts, a conical measuring tip and a body. The tip is equipped on the conical surface with six 2-element 90° tee-rosettes of measuring strain gauges (T1L – T6L, T1T – T6T). The compensating strain gauge TC is situated inside the tip but close to surface to achieve short temperature time response and good compensation during over-coring. TC is installed to special envelope which preserves it from mechanical stress. In the tip two 3.6V batteries are installed, too.

A holder, communication connector CAN 9M, check light emission diode (LED) stabilized power supply 5V and TTL/RS-232 interface are mounted on the top PCB board of the body – see Fig. 5 and Fig. 6. Blinking of LED indicates data transmission. It is useful for optical check of operation in autonomous mode.

On second PCB above A/D converter is placed. On third PCB a multiplexed strain gauge quarter bridge is placed. Fourth PCB is holder of CAN 26M connector only.

Body and tip are made and checked separately. Before grouting they are connected together by pair of connectors CAN 26. Finally free space is grouted with silicone rubber compound.

After finish of over-coring measurement the body is possible to separate from the tip by simple cut in the plane of separation – see Fig. 8. It is necessary to clean carefully communication connector CAN 9 because it has been submerged to wash water during over-coring drilling. After complete function test of electronic circuit inside body it is possible to connect a new conical tip and after grouting by silicon rubber compound to use the body once more. Economical reasons of this structural design are evident.

Electronic circuits are based mainly on CMOS technology chips. Therefore low current consumption 35 mA is achieved. Nominal capacity of battery B 6.4V is 950 mAh. It means more than 20 hours of autonomous operation are available in practice.

Diameter of probe is 56 mm (Diameter of borehole 76 mm). Top angle of cone is 60°. Diameter of middle circle of strain gauge rosettes is 38 mm.

PROCEDURE OF OVER-CORING EXPERIMENT ACCORDING TO 2nd GENERATION CCBO

1. Drilling, obtaining of drilling core for mechanical parameters of rock determination (Young's Modulus E, Poisson Ratio μ). Conical end of the borehole shaping, cleaning and desiccation. Visual check of conical surface quality using TV camera (Staš et al., 2005b).

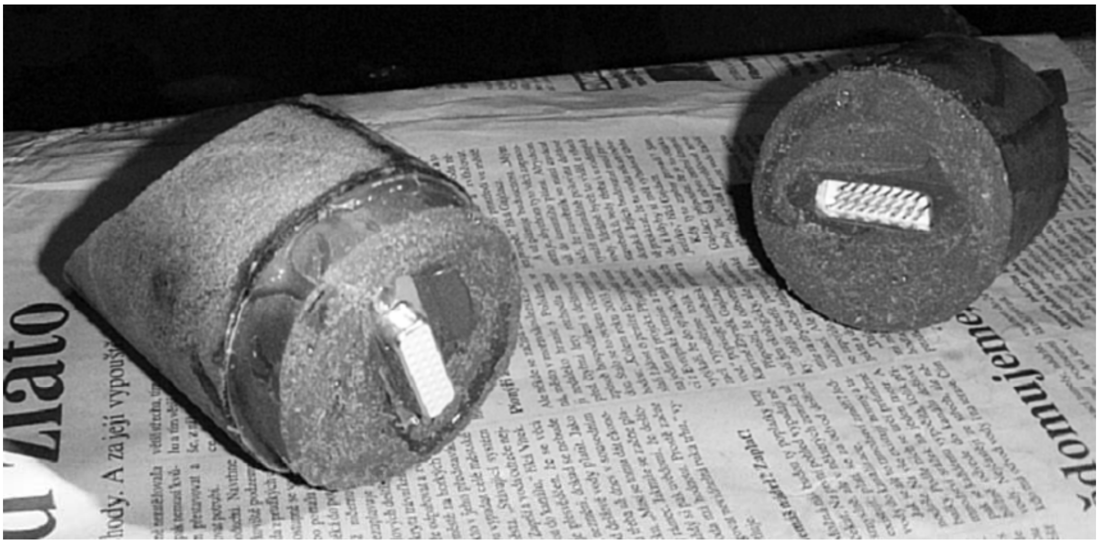

Fig. 8 The CCBO probe extracted from borehole after dissection in plane of separation.

2. Setting-up of measurement parameters on the CCBO probe.
3. Installation and gluing of probe, determination of probe orientation, test of probe functions, hardening of clay (The CCBO probe in "slave regime") - see Fig. 6. The CCBO probe is screwed to the end of insertion rod. Cylindrical box containing instrument "Pajari" for orientation of probe determination (Staš et al., 2005b) is seen below the screw holder. Canon connectors of communication line are inserted only (not bolted).
4. Check of function of the CCBO probe. Switching on the autonomous regime. Disconnection of communication line from connector CAN9M by means of tension in cable. Start of over-coring measurement. The CCBO probe switches off by itself if actual address of recorded data achieves Adr_max.
5. Over-coring drilling. Extraction of core with the CCBO probe from borehole.
6. Transmission of measured data from the CCBO probe to the interpretation computer.
7. Determination of E and μ, computation of stress tensor.

RESULTS OF TRIAL MEASUREMENT OF STRESS TENSOR

The first measurement of rock massif stress tensor has been made on 24th floor (depth 1200m below surface) in Rožná Mine, Czech Republic in October 2007. Workflow confirmed correctness of:

- Above mentioned procedure of over-coring experiment.
- Functionality of the CCBO probe and of the control computer program.
- Practicability of change of CCBO probe measuring tip in field conditions.

As an example, plot of measured data is presented in Figure 7. On the basis of recorded data it is possible to note, that the data scattering caused by mechanic vibration generated by drilling tool is comparatively low and accuracy of data is good. Accuracy of obtained data is possible to qualify according to plot of CAL. channel data.

The CCBO probe extracted from borehole after dissection in plane of separation is presented in Figure 8. The rest of overcored core is visible.

2nd GENERATION OF CCBM PROBE

Concept of 2nd generation CCBM probe is based on block diagram of CCBO showed in Figure 3. Following structural modifications are made:

- Connectors CAN 26 between body and tip are ommited.
- Battery B 6.4V is not installed. Probe is powered by communication cable.
- Connector CAN 9 is not used. Communication cable is connected directly to the modificated top PCB board of body.
- EEPROM data memory is not used in present model of CCBM probe.

Firmware of microprocessor MP is similar to firmware of CCBO probe (some commands for over-coring are omitted). Communication parameters are set to: 9600 bps, 1 stop bit, even parity. Even parity is used due to implementation of CCBM to the distributed control and measuring system based on Tedia Microunit – see Knejzlík et al. (2007) which communicates with even parity. There's no problem to modify communication parameters as well as communication protocol when needed.

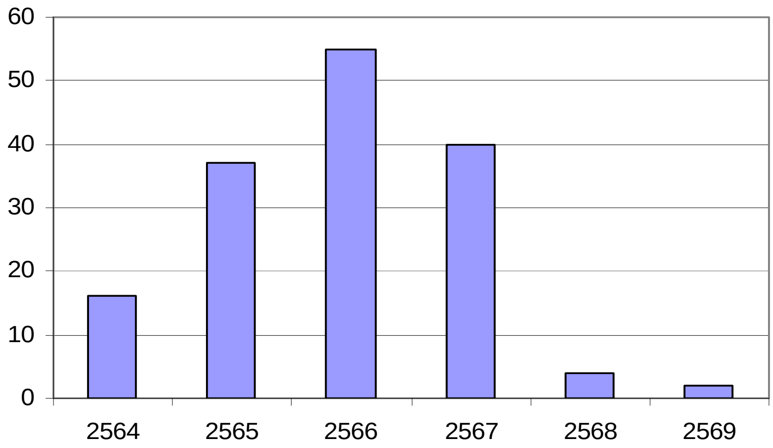

Fig. 9 Distribution of CCBM probe calibration channel CH[14]avg.

There are three principal modes of 2nd generation CCBM probe operation:

- Periodic manual reed of data using portable computer (Notebook, Psion).
- Remote data transmission.
- Implementation to the distributed control and measuring network.

Periodic manual reading of data using portable computer (Notebook, Psion) is regime close compatible with 1st generation of CCMB probes. Control computer sends command and the CCBM probe returns 32 byte of straight binary data. It is possible to use existing software for 1st generation CCBM with minimum adjustment. Principal improvement consists in automatic probe identification by reading of parameters stored in EEPROM PAR and in data scattering suppression reached by averaging, especially.

Remote data transmission is possible to realize using all known methods of computer communication. Standard RS-232 channel is possible to use for transmission up to 30m (depends of quality of line and level of disturbances). Greater distances are possible to reach using conversion to different communication standards (e.g. RS-485 up to 500 m, using LAN, virtual private network (Knejzlík, 2004) and/or using RS-232/Ethernet converter to reach unlimited distance). It is necessary to use fail-safe protocol for communication.

Implementation of the CCMB probe to the distributed control and measuring system is described in the paper (Knejzlík and Rambouský, 2008). Discussion about affecting accuracy of long-term measuring is published in (Staš et al., 2007a). Two CCBM probes (CCBM(2) and CCBM(3)) were installed into Jeroným Mine in November, 2007.

First results, evaluated from telemetric data show good stability of measured values and low level of data scattering caused by noise – see distribution of CCBM probe calibration channel data CH[14]avg (n_avg = 64) in Figure 9.

CONCLUSIONS

New, 2nd generation, of instrumentation for stress tensor measurement in rock massif by means of conical shape CCBO strain gauge probe was developed. This instrumentation enables to realize continual measured data recording in course of over-coring in using of domestic drilling machines.

Quite new is possibility of long-term stress tensor changes monitoring with long distance telemetric data transmission and/or possibility of implementation of CCBM probes to the geotechnical distributed measurement system.

Modified over-coring methodology and instrumentation functions were verified.

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REFERENCES

Kang, S.S.: 2000, Measurement and interpretation on stress history of a limestone deposit, A dissertation for Degree of Doctor of Philosophy Kumamoto, Kumamoto University.

Nakamura, N., Ohkubo, R., Obara, Y., Kang, S.S., Sugawara, K. and Kaneko, K.: 1999, Rock stress measurement for limestone open pit mine. In: Proc. Of 5th Int. Symp. on field Measurements In Geomechanics, Singapore, Balkema, Rotterdam, 375–380.

Knejzlík, J.: 2004, Data transmission from seismic stations via network AGNES using GSM-GPRS technology. Acta Montana, Ser. A, B, Vol. 1, No. 1, 73–76.

Staš, L., Knejzlík, J. and Rambouský, Z.: 2005a, Conical strain gauge probes for stress measurement, Int. Symp. ISRM Eurock 2005 - Impact of Human Activity on the Geological Enviroment, Czech Rep., Brno, Balkema, Rotterdam, 587–592.

Staš, L., Knejzlík, J. and Rambouský, Z.: 2005b, Stress measurement in rock massif using conical probe. Transactions (Sborník vědeckých prací Vysoké školy báňské – Technické univerzity Ostrava, řada stavební), Vol. V, No. 2/2005, 179–191, (in Czech).

Staš, L., Souček, K. and Knejzlík, J.: 2007a, Conical borehole strain gauge probe applied to induced rock stress changes measurement. 12th International Congress on Energy and Mineral Resources. Proceedings. Oviedo: Consejo superior de celegios de ingenieros de minas, 2007, 507–516.

Staš, L., Souček, K. and Knejzlík, J.: 2007b, First results of conical borehole strain gauge probes applied to induced rock mass stress changes measurement. Acta Geodyn. Geomater., Vol. 4, No. 4(148), 77–82.

Knejzlík, J. and Rambouský, Z.: 2008, Recent solution for distributed control and measurement system at the Jeroným Mine – Modular System. Acta Geodyn. Geomater., Vol. 5, No. 2 (150), 205–212.

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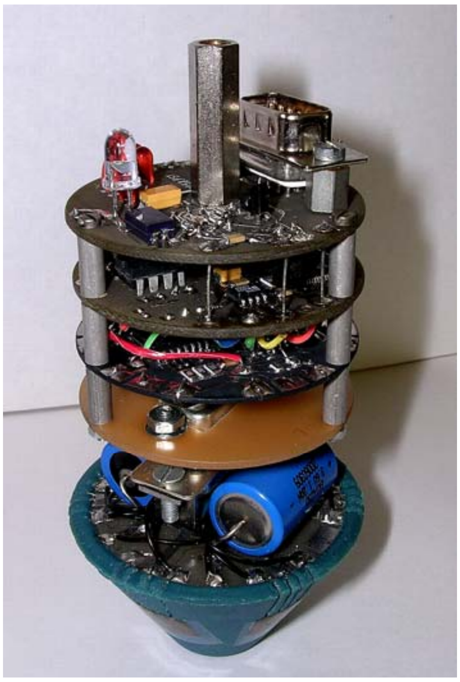

Fig. 5 Mechanical design of CCBO.

Fig. 6 Preparing of CCBO installation to borehole. Separation plane ismarked.

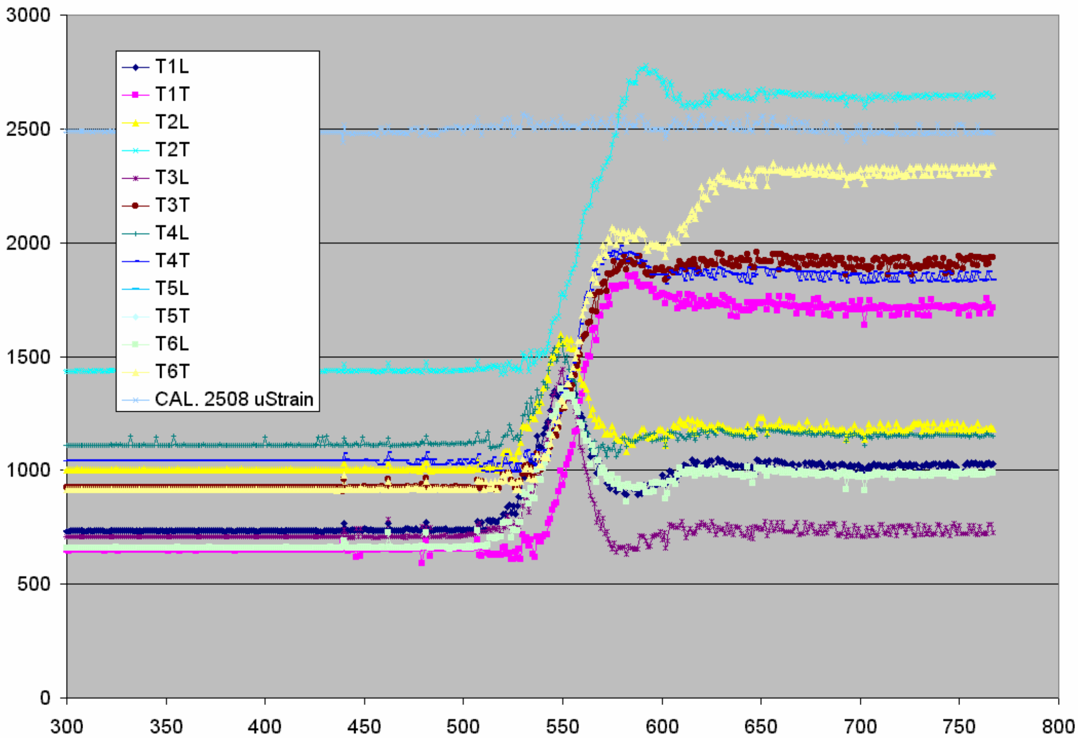

Fig. 7 Plot of measured data. Over-coring experiment in Rožná Mine.
X-axis: ordinar number of measurement, sampling interval Per = 3s.
Y-axis: deformation [μStrain]