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UTILIZATION OF CONDUCTIVE YOKOHAMA RUBBER FOR CONSTRUCTION OF PRESSURE TRANSDUCERS

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Abstract. For the purpose of experimental analysis of stress state in geotechnics by the method of measuring the changes of stress on physical models pressure transducers of completely new construction were designed and tested. These transducers are based on the properties of pressure-sensitive rubber of YOKOHAMA RUBBER. The results of the tests have shown the usability of the newly designed transducers for these purposes.

1. Introduction

The knowledge of the structure stress state is the fundamental requirement on the judgement of its safety. In geomechanics the distribution of stress in the environment of the underground structure and monitoring the stress changes in time are also very important. Beside numerical method also physical models are utilized for this purpose in a considerable measure (Skořepová, 1991). By these methods large territories are modelled, which causes a considerable decrease of the model in comparison with reality. This imposes demanding requirements on experimental methods, as well as measuring devices.

One of these methods, which is used for measuring of stress state on physical models constructed in connection with solution of various geotechnical problems, is measuring by means of pressure transducers equipped with resistance strain gauges, or contingently semiconductor strain gauges. The transducers dimensions in the model then represent particular non–homogeneities which may influence negatively the results of the model experiments. That is why the basic general requirements on the transducers determine the transducers dimensions to be as small as possible within the condition of the required sensitivity. The transducers should have plane character which causes the necessity to use another transfer of pressure on the output signal (Volf and Holý, 1993). These reasons, beside the economic reasons and the availability of conductive rubber used for tactile sensors made us to use this rubber in geomechanics as well.

Development of the transducers was sponsored by the grant of the Grant Agency of the Czech Republic no. 205/94/1788 "Application of experimental stress analysis in geotechnics for minimization of structure failure".

2. The Principle of Measuring the Stress State in the Model

During the construction of physical models the transducers are put into the model material in selected places. As the consequence of the changes of affecting forces during the experiment (application of outer loading, simulation of mining advance, etc.) the material surrounding the transducers is being deformed and the forces are transferred from the model body on the inserted transducers. The deformation of the transducer is the function not only of the model loading considering the non–homogeneities. These non–homogeneities are evoked by the transducers themselves, but the deformation also depends on rigidity and on the final dimensions of the transducer, on mechanical–physical properties of the used model material and to a considerable extent on its contact with the surrounding material (Kohoutek & col., 1977). Because of this reason it is necessary to carry out calibration of the transducers after their location in the model.

The methods used during calibration are following: after completion of the model construction gradual loading and discharge of the model by outer forces in several cycles are carried out and on a suitable device (data–acquisition and automated measuring equipment) the data of the transducers are recorded. Time interval is chosen depending on the model material. The data having been collected in this way determine the calibration curves for transducers; these curves serve as bases for evaluation of the changes of the model stress state changes in the environment of each transducer during the model experiment (Vencovský and Málek, 1994).

High requirements are put upon the accuracy of measuring the stress state in the models. The model is in fact a many times reduced reality (the scale downs are chosen in dependence on the problem being solved from 1:50 to 1:1000). That is why the entire measuring chain including all beginning with the pressure force transducers and ending with the memory medium for registration of the measured values must fulfil the high accuracy requirements. Most of currently utilized measuring devices (e.g. Unilog 2500 made by PEEKEL, used by us) fulfils these requirements and that is why the reliability of the measured data depends first of all on the suitability of the used transducers.

The transducers used for measuring the stress state of physical models are judged from several points of view. First of all it is the transducer sensitivity, i.e. the capability to register even very small changes of the stress state of the model, the extension of the transducer and its long–term time stability. An important role is played by the size and the shape of the transducer. The transducers in a model are strange elements and that is why the transducers were miniaturized. From the viewpoint of the behaviour of the system "transducer - model material" the speed of the transducer reaction to the changes in loading and the reproduceability of the measured data are judged as well.

3. Construction of the Transducer, Properties of the Rubber

a) Measuring Devices

The design of the described proportional transducer allows to reach subminiature dimensions and a perfect resistibility to multiple overload and shocks and also a sufficient safety degree in explosive surroundings. The sensor indicates not only simple contact, but it can give quantitative information. The sensors are made of Japan conductive rubber CS57–7RSC (Ishikawa and Shimojo, 1982; Technical documentation ...)

Characteristics of Conductive Rubber

Colour:	black
Thickness:	0.5 mm
Tensile strength:	1.9 $\mathrm{Nmm^{-2}}$
Elongation at break:	220 %
Operation temperature range:	−40 °C±100 °C
Shear strength:	7 $\mathrm{Nmm^{-2}}$
Maximal pressure load for linear limit:	600 kPa (for repeating loading of 1 million cycles)
Chemical Properties:	Resistance to gas as ozone or chemicals is equal to the usual silicone rubber
Superior:	in aging, thermal and chemical resistance to many corrosive substances and ozone, chemically inert
Useful:	water, methanol
Affected:	acetone
Not useful:	n–hexane, toluene, trichloroethane
Dangerous:	By absorbing the oil as lubricating oil, the pressure sensitive property is broken

The original sensors PMT 1.4 (Fig. 1) were designed and examined (Volf, 1993; Volf and Holý, 1994). In the sensor the conductive elastic material 6 lies between a couple of electrodes 4 and 5. One of these electrodes is placed on the basic plate 3 and the second one on the elastic cover layer 1. This layer transfers axial pressure force to the conductive material 6. The distance insert 2 serves for an adjustable working range of the sensor and for the protection of the conductive material against overloading, too. The transducers are without mobile mechanical elements. For better conditions of transducer contact with model material, very thin metal leaves were stuck on the both surfaces of the flat sensor.

For verification of application in practice of transducers with conductive rubber layer with the thickness of 0.5 mm were designed and tested either in general (Volf, 1994) and for geomechanics.

The relation between the resistance change and the pressure force for sensor PMT 1.4 (the dimension of one sensor is 4×4 or 8×8 mm) is given on Fig. 2. The relations between the load of the transducer and the deformation of sensing elements are not linear in all range. The output electrical signal could be linearized

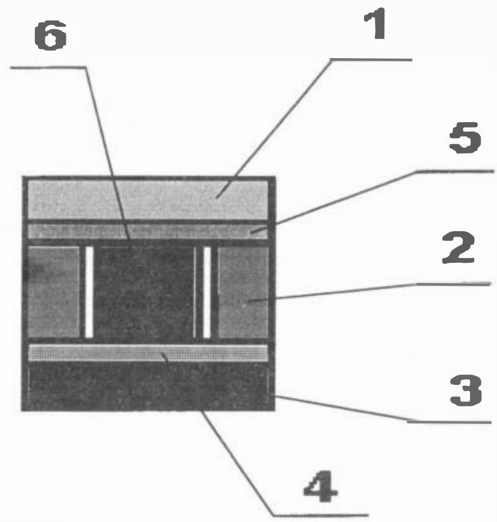

FIG. 1. The construction of PMT 1.4

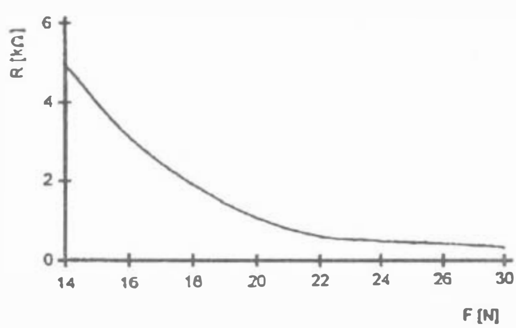

FIG. 2. The dependence $R = f(F)$ for PMT 1.4

by suitable choice of electronic circuits and by computer. The dependence on resistance to supplied current (Fig. 3) as well as to temperature (Fig. 4) and number of loading cycles (Fig. 5) were also examined. The definite characteristics has two branches given by critical temperature (approx. −30 °C, Fig. 4). At −30 °C and below, elasticity and conductivity are impaired, but the material will regain original properties, when is warmed to higher temperature (Volf and Holý, 1995).

b) Practical Experiences

The response of resistance to pressure is so quick so that time dependent changes of resistance could be quite neglected. But by static loading some phenomenons have appeared. For this reason short and long lasting measurement were performed, with voltage and current electrical feeding of the transducer. Voltage feeding gives practically constant differences between loading and unloading. The resistance

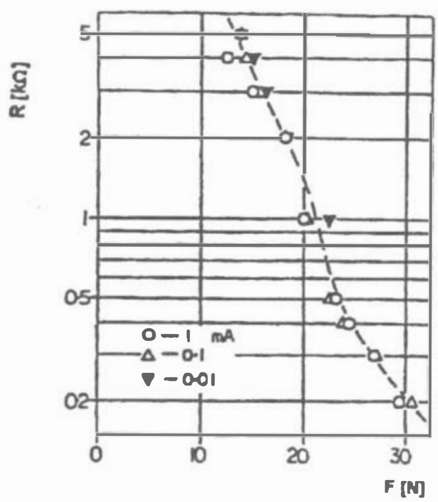

FIG. 3. Influence of supplied current

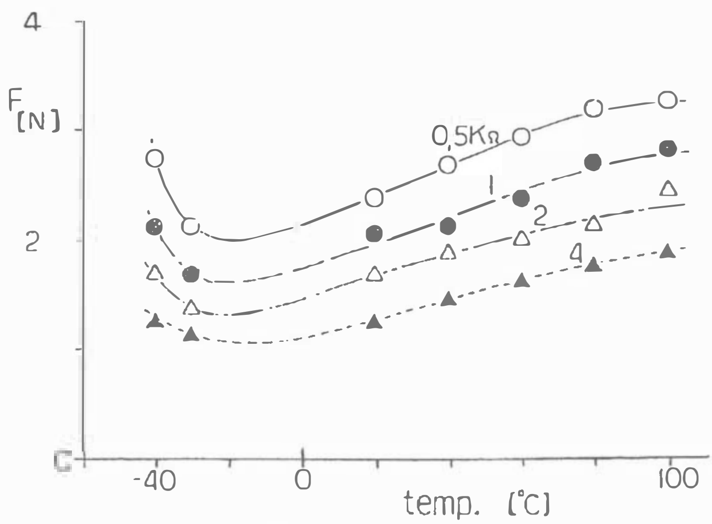

FIG. 4. Temperature dependence

value is the time dependent on a flow aiming to the same limit (with accuracy of 2 %).

For dynamic loading with the basic frequency of about 0.1 Hz starting part of the measured characteristic (Fig. 6) can be used. For a long lasting loading of static character (Skořepová, 1991) one must take into account time dependent relation of deformation of conductive rubber under pressure (exponential course), which influences the changes of the transducer resistance according to Fig. 6. The constant value of the transducer resistance is achieved after approximately 2 hours of

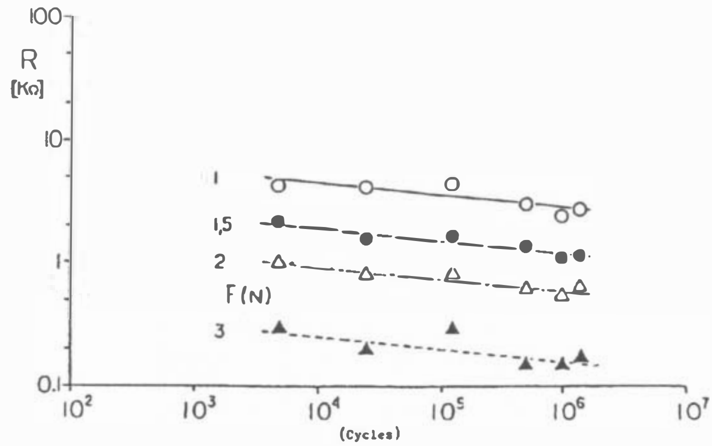

FIG. 5. Loading cycles test

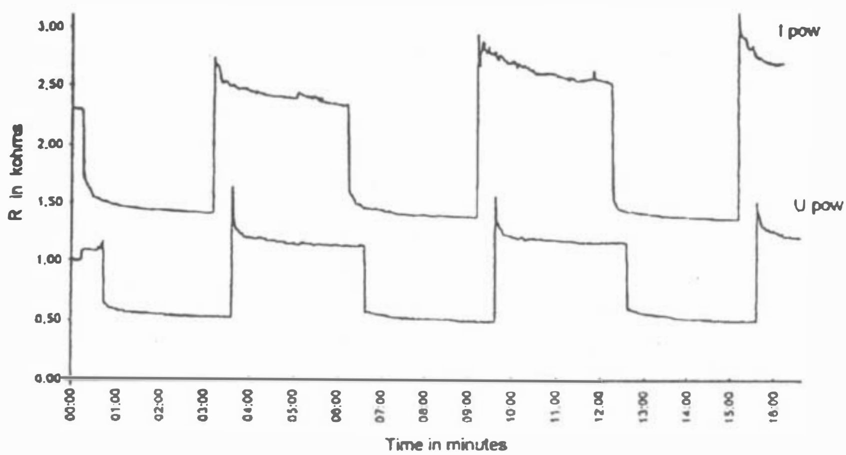

FIG. 6. Test of transducer resistivity changes

operation (Fig. 7). The constants, taken for this time, can be used for long lasting measurements.

The integral part of the research into the pressure transducer on the base of pressure sensitive rubber was the technological aspect as well. The transducer, as mentioned above, is equipped with electrodes which are both mechanically and electrically connected with the rubber layer. That is why the comparison of resulting properties of these transducers were carried out for various kinds of conductive glues and for the test the most suitable glue was used. In the same way the protection of the whole transducer against moisture and the effects of fats and oils was observed. These fats and oils are frequently contained in model materials substituting the

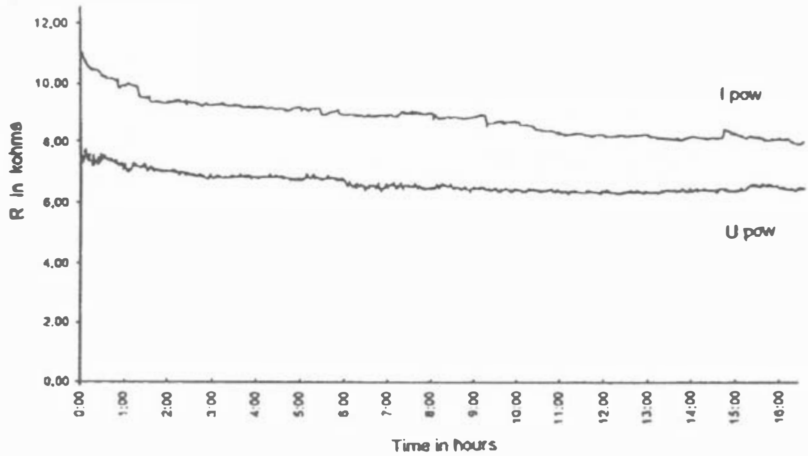

FIG. 7. Test of stability $R(t)$

rock environment in the models.

4. TESTING OF THE TRANSDUCER FOR UTILIZATION IN PHYSICAL MODELS

a) Miniaturization of the Transducer

The effort for the construction of a transducer which would be as small as possible lead to production of flat transducer with dimensions 4×4 mm. However it has been shown, that it was technically impossible to situate this transducer with sufficient accuracy in the chosen position in the model (with measuring surface oriented in exactly horizontal or vertical level). Further miniaturization also meets with the problem of the technological method of their construction. That is why transducers of dimensions 8×8 mm and 10×10 mm were produced as optimum. These were later exposed to further tests.

b) Time stability of the transducer signal value, the transducer sensitivity

For verifying the time stability of the measured data of the transducer during its constant loading we tested in test model three transducer PMT 1.4 of dimensions 8×8 on the base of the Japanese material of Yokohama Rubber (Technical documentation ...), together with three semiconductor transducers TM 440 Type F (made by Tesla Ltd. Valašské Meziříčí), which are commonly used for the purpose of measuring the stress in models and which during their utilization showed very good results. All tests were carried out with transducers placed into a chosen model material (mixture of sand+bentonit+fat A00). The way of situating the transducers and the dimension of the used modelling device are patently obvious in Fig. 8. In all other figures (Fig. 9 – 12) the tested transducers PMT are marked S_1, S_2, S_3 and semiconductor transducers TM 440 type F are marked S_4, S_5, and S_6.

After connecting the transducers to the automated measurement equipment in 5 minutes intervals the data of all six transducers during 6 days were recorded

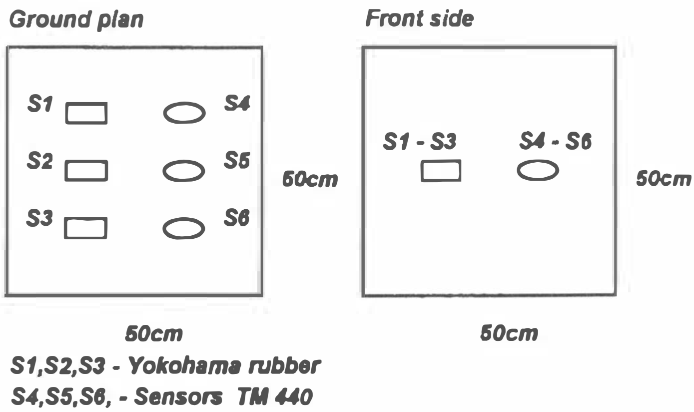

FIG. 8. Location of the transducers in the model stend

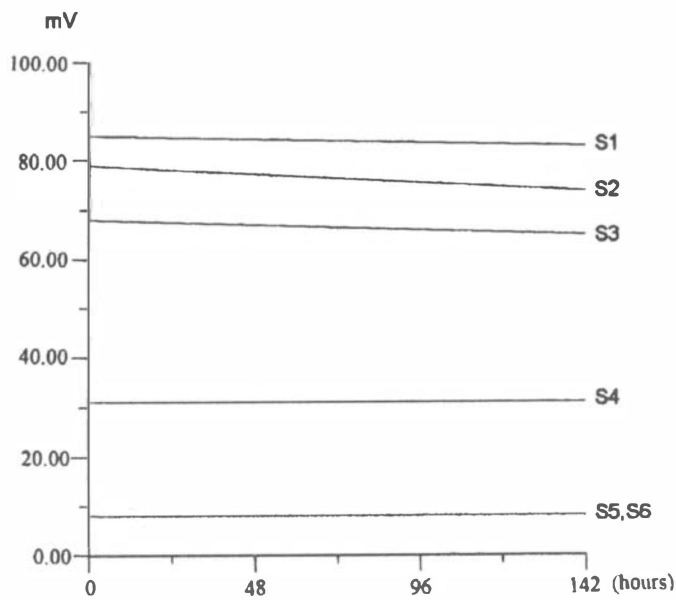

FIG. 9. Control of the time stability of signal of the transducers

(Fig. 9). Although the tested transducers show on the automated measuring equipment a slight decrease in read values of the output voltage from the transducer in comparison with semiconductor transducers, with regard to the dynamics of the read values in consequence of the change in the transducer loading (See further at the reaction of the transducer to the change in loading), this decrease does not seem to be important. With the ordinary length of the model experiments (it usu-

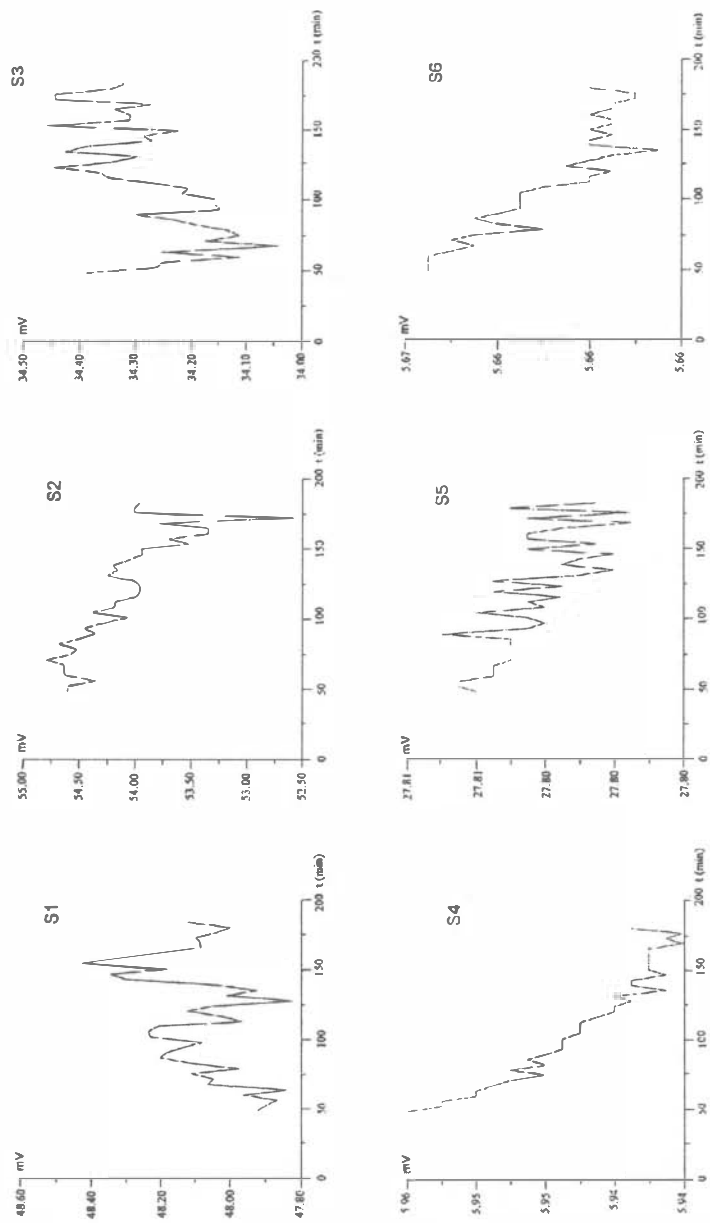

FIG. 10a. Detail record of signal of the transducers; the loading of transducers 0.76 kPa (registered immediately after the loading change)

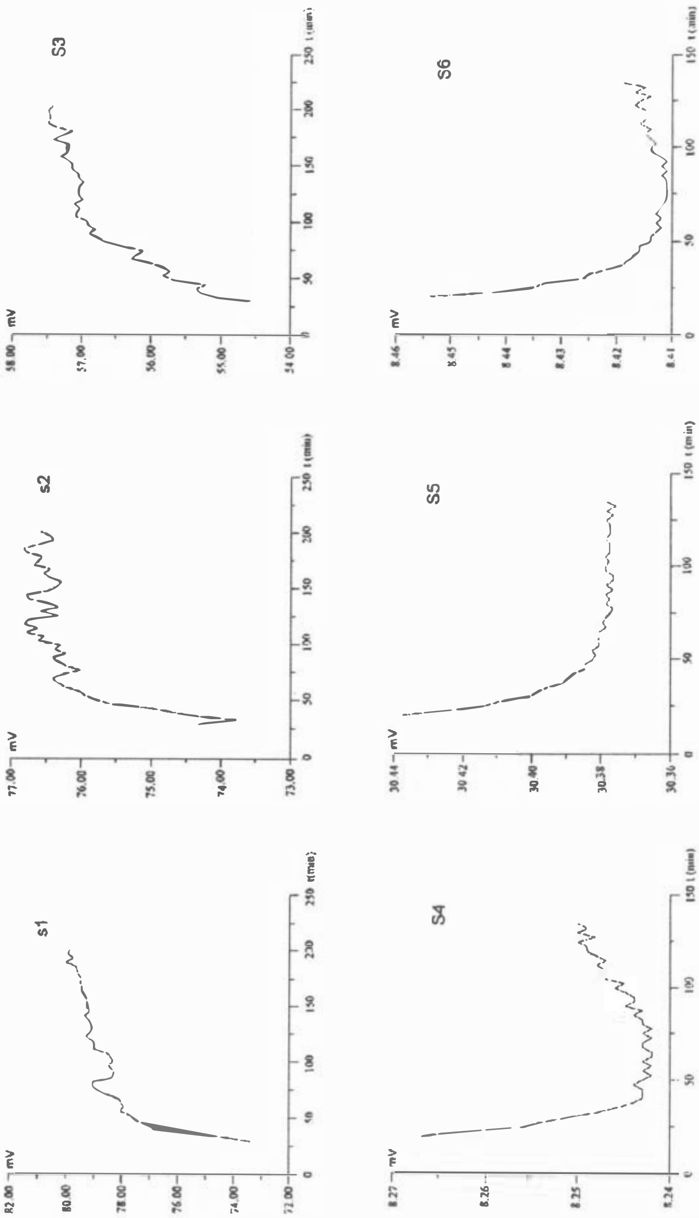

FIG. 10b. Detail record of signal of the transducers; the loading of transducers 25.0 kPa (registered immediately after the loading change)

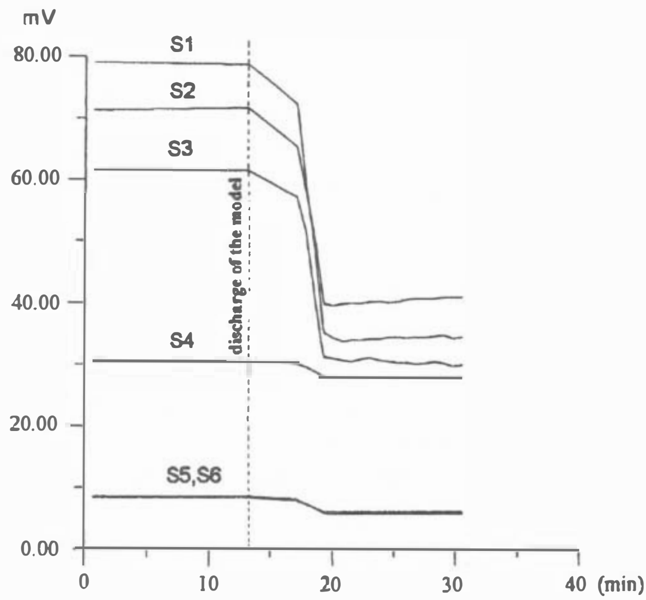

FIG. 11. Speed of the transducers reaction to loading changes – stress lowered from 25 kPa to 0.76 kPa

ally does not exceed 12 hours) and within the method of transducers calibration in the model this decrease should not influence the accuracy of the model experiment results. From a more detailed record of the measured data it is then possible to observe the character of the transducer noise, which is realized either with minimum loading (Fig. 10a) – the transducers were affected only by the stress given by mass of the model material 0.76 kPa, or given by the outer loading of 25 kPa caused by metal clump weights placed on the surface of the model (Fig. 10b). It is necessary to notice that the change of the signal of the tested rubber transducers as a consequence of their loading, which can be named as the transducer sensitivity, is on average 10 times larger than at semiconductor transducers (26.0 in comparison with 2.6 mV).

c) The Reaction of the Transducer to Loading Changes

For determining the transducer reaction to the loading changes the testing model with transducers was gradually loaded and unloaded and during these processes both the speed of the transducer reaction to the loading changes and the size of the changes in the read values were observed. Concerning this speed of the transducer reaction this speed is comparable for both transducer types (Fig. 11) and is sufficient for utilization in models. In Fig. 12 where can be found the results of the model test when the model was being gradually loaded in three identical cycles.

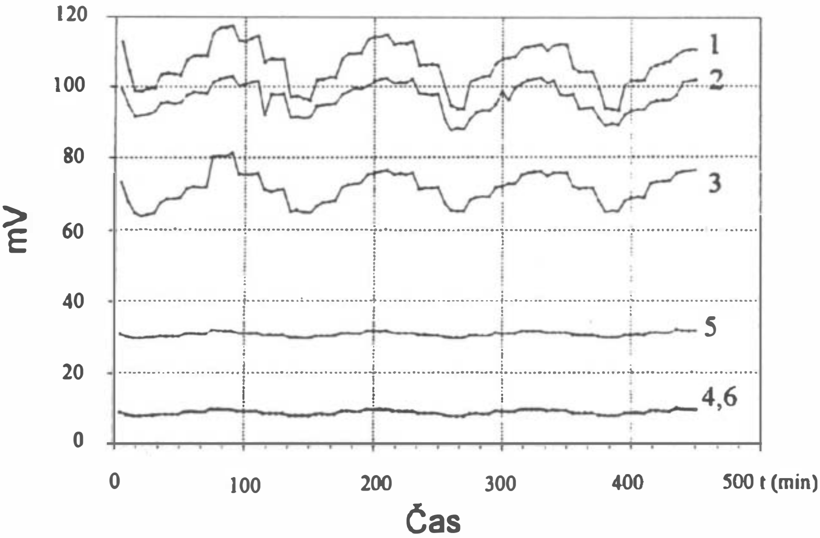

FIG. 12. Reaction of the transducers to loading changes. Gradual loading and unloading in three cycles. Values of outer loading in cycle: 0, 6.64, 13.28, 19.92, 27.90, 19.92, 13.28, 6.64, 0 (kN)

d) Reproduceability of measured data

All tested properties of the system "transducer – model material" in preceeding points are fully apparent during a model experiment which is being carried out as described above. This means that first of all the calibration of the transducers in the model is carried out and the model experiment follows after; in this experiment the changes of stress state in the place of the location of each transducer are evaluated on the base of derived calibration curves. That is why for the next testing model the classical calibration measurement with three loading cycles with gradually increasing loading was carried out (Skořepová, 1975). In Fig. 13 there is the description of calibration cycles for transducers. Again the first three tested transducers ($s^1 - s^3$) are PMT 1.4, $s^4 - s^6$ are semiconductor transducers TM 440, but type E, the sensitivity of which (the change of signal in consequence of the change in the transducer loading) is of the same value range as rubber transducers. From the comparison of the loading cycles it is obvious that the rubber transducers under the condition of locating in the model material show even double hysteresis than semiconductor transducers and slightly higher non-linearity. However both data are within the limits of technical accuracy. Whereas at semiconductor transducers during every further loading cycle the read values of the automated measurement equipment under the condition of full discharge of the model increase, which is caused by constant deformation of the model material, rubber transducers do not have this tendency. We can often see a completely different phenomenon, i.e. the read values decrease during further loading cycles. On the whole the process of the

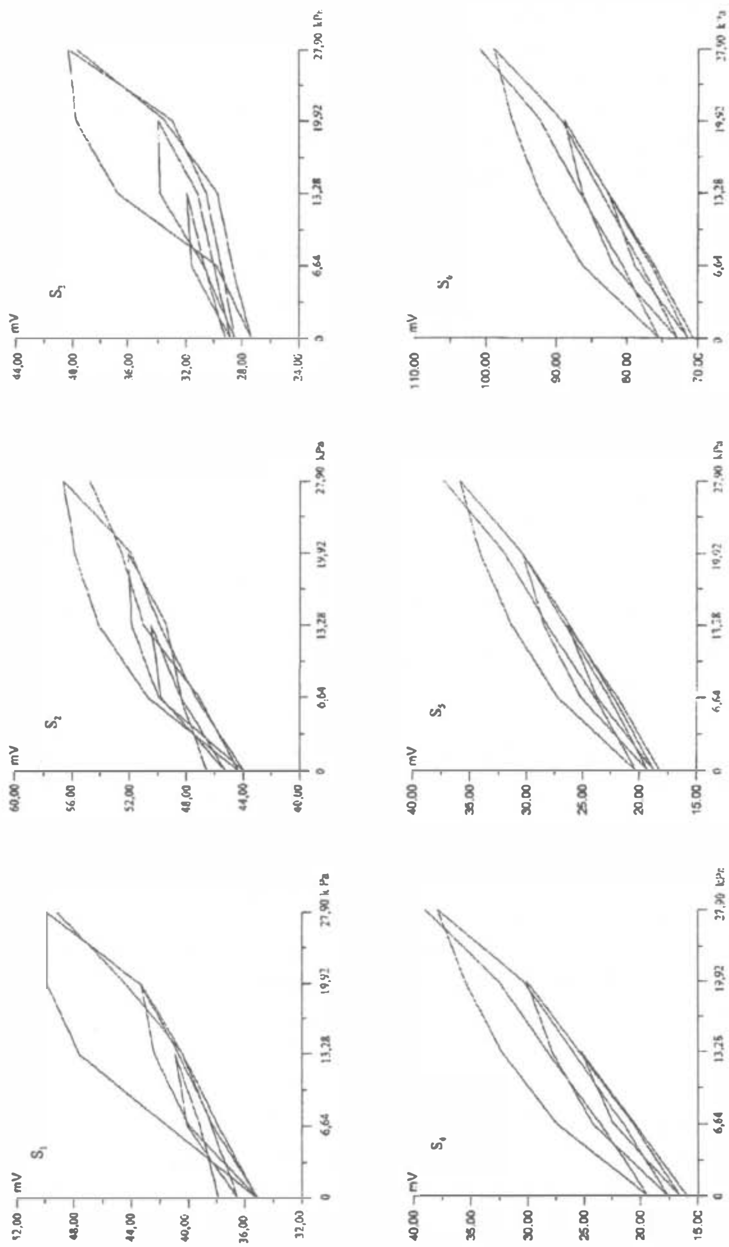

FIG. 13. Calibration of the transducers in the model – dependence of read values on outer loading of the model

calibration diagrams, especially in case of small loading values, is not as regular as at semiconductor transducers.

For the purpose of finding whether this tendency is completely incidental, or if it is given by the transducer construction, or the material used for the production of the transducer, a new model experiment was carried out; this experiment was realized identically with the preceeding one. In Fig. 14 there is the time series of read values for this model experiment.

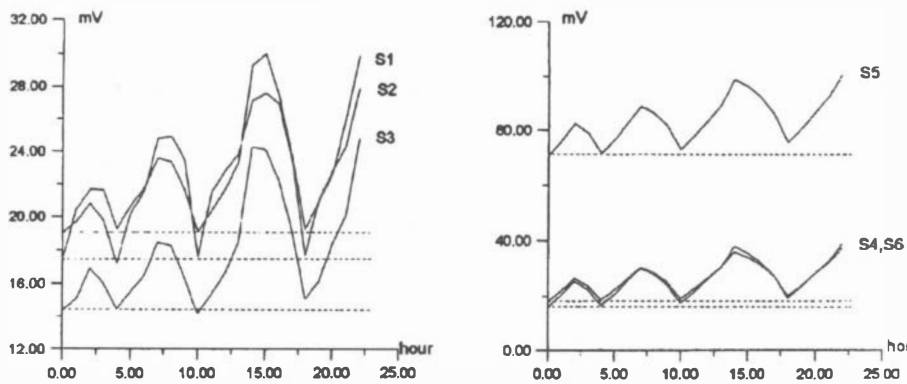

FIG. 14. Calibration of the transducers in the model – reaction of the transducers to loading changes

It starts to seem that in case of small loading values the transducer PMT 1.4 are not able to react accurately to the loading changes. However this defect completely disappears under higher loading when the transducers measure within reliable limits. During the model experiment the calibration of the transducers was supplemented with other incidentally chosen loading phases which were utilized for so called "boomerang test", when the stress state of the model in these phases were considered as unknown quantity and was in turn calculated from the results of the calibration. Under higher loading values the transducers PMT 1.4 have reached results comparable with transducers TM 440.

5. CONCLUSION

If we conclude both qualitative and quantitative values of the results for tested pressure transducers based on the properties of the pressure–sensitive rubber YOKOHAMA RUBBER, later on the technological point of view, and last but not least economic point of view (the cost of the transducer PMT 1.4 is more than 35 times lower than currently used semiconductor transducers), the tested transducers are fully usable for measuring the changes of stress in physical models in geomechanics. The transducers can be constructed within the wide extent of dimensions beginning with dimensions 4×4 mm and ending with total–area transducers with the possibility of detecting integral values of pressure, or under the condition of matrix arrangement of electrodes (Volf and Holý, 1994) the distribution of pressure throughout the area of the transducer.

On both working sites participating in the construction and in testing the pressure transducers on the base of resistance–sensitive rubber (in the Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic and the Faculty of Mechanical Engineering, Czech Technical University in Prague) in relation to the grant of Grant Agency of the Czech Republic number 205/94/1788 "Application of experimental stress analysis in geotechnics for minimization of structure failure", solving teams were constituted; these teams were not large in number of members, but all of them had wide experience in both the technology and the application of the pressure–sensitive transducers. Large verifying of geometrical, technological and operational properties of pressure transducers on the base of resistance–sensitive rubber YOKOHAMA RUBBER, carried out in both working sites during the solution of the grant project (Skořepová and Holý, 1994) gives an explicitly positive answer to the question of usability of such transducers for model experiments in geotechnics. The basic research into these transducers is now considered to be completed. It would be still suitable to verify the statistical parameters of the resistive values and described characteristics of a larger set of transducers and that is why the solving team intends to continue in its work. The members of the solving team also consider about the possibility of utilization of the transducers on the base of resistance-sensitive rubber for measuring the transversal deformation on the testing rock samples and for their application in situ.

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