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ASSESSMENT OF THE STRESS STATE OF A PHYSICAL ROCK MASS MODEL BY MEANS OF TENSOMETRIC SENSORS

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ABSTRACT. Determination of the stress state of a physical rock mass model by means of tensometric measurement has been a long-term research problem of the Modelling laboratory of the Institute of Geotechnics (Czech Acad.Sci.). At present time, the study of this problem reached some important results: High-quality, reliable and dimensionally acceptable tensometric sensors are available; they cooperate with the automatic central PEEKEL, which enables the recording of tensometric data to be effectuated for upto 400 sensors. Two computing programs, linked together, have been developed for processing these data and automatic evaluation of the stress state of the physical model in the neighbourhood of each sensor. The functionality of these programs has been tested by several model experiments. The obtained information confirms the possibility of routine application of both programs as well as their convenient ability to extrapolate the stress values lying outside the range of the realized calibration.

1. INTRODUCTION

Special pressure pickup elements for the measurement of the stress state at selected points of a physical rock mass model have been developed in the Institute of Geotechnics (Czech Acad.Sci.), which can be inserted directly into the modelling material during the model construction. In the course of a model experiment, the deformations of the model material are transferred to measuring sensors (transducers) fitted with electrical resistance or semiconductor tensometers. Data from these sensors are recorded in a suitable storage medium and are then used for the determination of both the model deformations and its general stress state. The development and the preparation of such sensors were pursued by Jurečka (1978, 1982, 1989).

The Institute of Geotechnics has actually, at its disposal, sensors DO14X, fitted with self compensated foil tensometers Philips, type PR 9832K/10 FE with resistance $R = 600 \pm 0{,}25\,\%$ and sensors TM440 fitted with semiconductor pressure pickup elements (Jurečka 1978, 1982, 1989).

Both mentioned sensor types are functional and reliable and they guarantee a high precision of measurements. The nonlinearity of the sensor data in dependence of their deformation is lower than $\pm 1\,\%$ within the temperature range of 0–35 C°.

However, the application of these tensors to the above- mentioned purposes encounters certain problems, considering, as it will also result from further parts of this article, that properties of sensors situated inside the model mass differ entirely from their original properties as linearly elastic systems.

The assessment of the stress state of a physical model at the deposition site of a certain sensor on the basis of data from its pickup element is conditional on the formulation of a rather complicated evaluation method, which is, in principle, always based on calibration measurements. Such measurements should be understood, in this connection, somewhat differently than usual. Their purpose is to determine the behavior of each sensor with regard to the

- chronology of its subsequent loading and relieving,
- necessary assumption of the accumulation of non-elastic strain,

and to acquire, in this way, information enabling the stress of the model material to be determined also for such sensor data, which considerably exceed the data for maximum calibration load.

2. Fundamental information on properties of sensors

2.1 Free sensor

The behaviour of the so-called free sensor, i.e. a sensor, which does not contact any medium except the air, which consequently is not – in this case – inserted into the modeling material, is characterized by almost linear dependence of the data l of its pickup on its load s.

The loading function

$$l = l(s)\,, \tag{1}$$

which can be written in the form of

$$l = l_0 + k.s \tag{2}$$

can be determined simply as a linear regression function from the suitably arranged calibration measurement, while, in so doing, the time sequence of the subsequent loading and relieving of the sensor must not necessarily be considered.

2.2 Fixed

The behaviour of a fixed (restrained) sensor, i.e. of a sensor situated, in this case, inside the modelling material of a physical model, is considerably more complex and its calibration results (as a free sensor) cannot be used for the stress assessment. During the calibration of a free sensor, the boundary conditions (1st boundary value problem of the theory of elasticity) are force-dependent, while boundary conditions for a fixed sensor are deformational (2nd boundary value problem of the theory of elasticity). The fixed sensor reacts to a certain deformation, which is a function not only of the load on model, but also of the rigidity of the sensor and mechano-physical characteristics of a modelling material. This means, for example, that sensors with the same characteristics, inserted into the geometrically identical models, but differing by the module of elasticity of the modelling material, will exhibit different data even at the same load of models. Sensors "softer" than the modelling material will be partly relieved within the model (a vault will from above them) and, on the contrary, the "stiffer" sensors will be surcharged (Málek 1977). This is the reason, why sensors of different rigidity have been developed and, for a certain material, sensors of possibly optimum properties are chosen.

.The assessment of the stress state of a physical rock mass model is therefor conditional on the calibration not of the free sensors, but on the calibration of the elastic-plastic system: sensor + modelling material, which will be further denoted by the symbol SM. Such a calibration can be realized on the basis of an adequately arranged calibration measurement exclusively on a pressure modelling stand, which enables, in the given case, the loading and relieving of the whole model to be changed in the required manner. The arrangement of the calibration procedure must involve the hitherto known properties of the SM system, which could be summarized in several publications (Vencovský 1990, Filip 1987).

1. System SM is elastic-plastic. After loading and subsequent relieving, the system SM does not return into the original geometrical shape. The non-reversible permanent deformation d of the SM system depends on its momentary load s and on the mechano-physical properties of the modelling materials. Generally
$$d = v(s)\,. \tag{3}$$
2. The loading function (1) is not unique (single-valued) and the determination of stress s for a certain sensor value l must be made with regard to the so-called attribute of the value l. In principle, two characteristic parts – branches – of this function may be differentiated:
$$l = p(s) \tag{4}$$
for the case that the value l is increased in time, i.e. this branch has the attribute of "surcharge", and
$$l = o(s) \tag{5}$$
for the case of a value l that decreased with time, thus belonging to the branch of "relieving".
3. Functions (4), (5) can be considered, according to point 1, in forms
$$p(s) = v(s_p) + f(s)\,, \tag{6}$$
$$o(s) = v(s_p) + g(s)\,, \tag{7}$$
where $v(s_p)$ is the permanent deformation of the SM system after its precedent loading s_p or, eventually, after its precedent loading by monotonously increasing values s up to the value of s_p.
4. It is known from experience (Filip 1987) that functions (6), (7) are purely monotonous and increasing, acquiring exclusively non-negative values.

This information together with those from chapter 2 are very important for determination of stress s_i of the SM system in relation to the tensometric information l_i, which is found, at the moment t_i in the time series arranged in the ascending sequence: $t_i < t_{i+1}$. If

$$l_i < l_{i+1}\,, \tag{8}$$

the point is that the stress s with its attribute "surcharge" (+1) by means of the function (6) should be determined, and viceversa, if

$$l_i > l_{i+1}\,, \tag{9}$$

the stress of the SM system should be determined by means of the function (7), because the value of l_i has the attribute of "relief" (−1). The indicated application of functions (6) and (7) has only a general significance. In reality, the derivation of stress corresponding to data of a tensometric time series is a much more complicate problem (see chapter 3).

2.3 Calibration

Calibration measurements necessary for the derivation of regression functions (6) and (7), are based on a successive loading and relieving of a model with fixed sensors in the way illustrated by Fig.1. The model is loaded by several consecutive, gradually increasing loads (points 1,2,3,4) up to the load at the break point (point 4), after which a monotonously decreasing sequence of reliefs follows up to the state of complete relief (point 7 = V_1). After attaining the complete relief, the model is loaded again monotonously with increasing loads up to the load at the break point, which defines the so-called duplicating point, an so on until the next, suitably chosen break point is achieved (point 11). The first break point and the corresponding (to it) duplicating point participate in the determination of the so-called nodal (common) point H_1. The analytical regression function, interpolated by the least-square method through all points with the attribute of relief so that it would pass the points V_1 and H_1, let be called the <u>relieving</u> branch (hatched). Let then the analytical regression function, determined in similar way, but with the attribute of surcharging, be called the <u>surcharging</u> branch (dotted) of the calibration scheme. Both branches run through points V_1 and H_1 and form the 1st <u>calibration loop</u>. After attaining the second break point (point 11), the loading and relieving of the model is organized so to yield the 2nd <u>calibration loop</u> (nodal points V_2, H_2) and, eventually further calibration loop (Fig.1: 3 loops).

The calibration procedure organized in such a manner leads further to the derivation of two calibration characteristics. This is, above all, the so-called <u>main branch</u> of the calibration scheme, which is defined by analytical regression function

$$l = h(s) \tag{10}$$

interpolated by the least-square method through all break and duplicating points, as well as through all other points, which do not participate on the determination

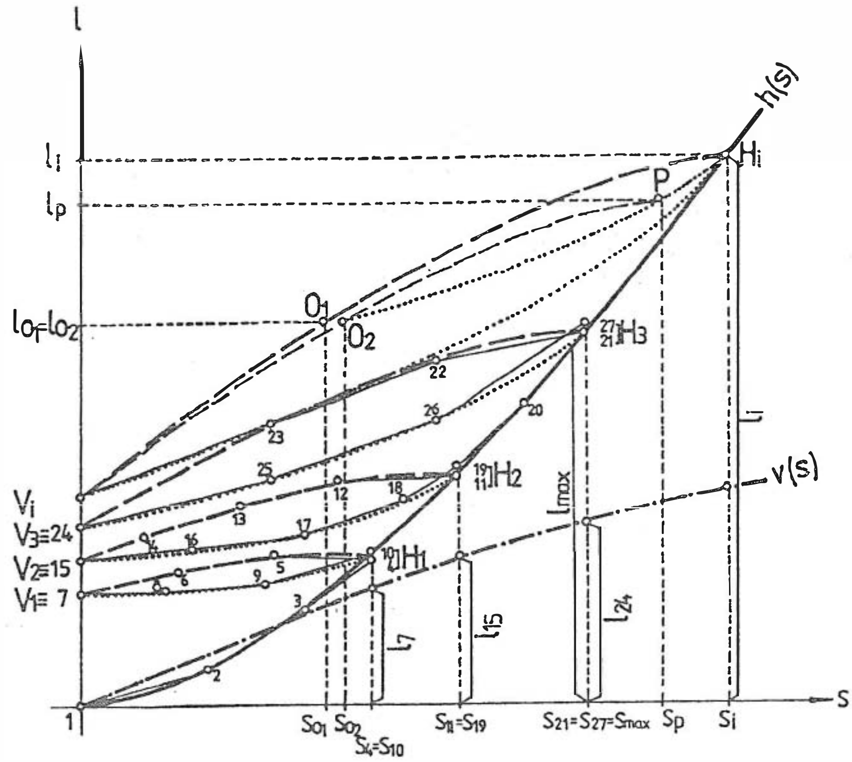

FIG 1.. Layout of the calibration measurement

of relieving or surcharging branches (Fig.1 — strong solid line). The second basic characteristic is then the so-called secondary branch of the calibration scheme, which is defined by the analytical regression function

$$l = v(s) \tag{11}$$

running through the origin of the coordinate system s, l and joining at the best the points, whose abscissae s equal the loads in break points and whose ordinates equal those of nodal points of the V-type (points: $(0,0)$, (s_4, l_7), (s_{11}, l_{15}), (s_{21}, l_{24})). The secondary branch defines continuously the non-elastic strain (permanent deformation) of the model after its pervious loading.

It should be added to the described calibration procedure that the sensor data for a certain stress state of the model are not recorded before a certain, suitably chosen time (i.g. 10 min.), was allowed to elapse, supposing that the model deformation process will stabilize during that time and conditions of the so-called quasi-static deformation state will prevail.

3. Evaluation of tensometric measurements of the stress conditions of a model

3.1 Basic rules

The following short specification of rules for the interpolation of load s_i for the value of tensometric data l_i of a certain system SM_i resulted from information acquired during the long-term development of the given problems and which were summarized in (Vencovský 1990, Filip 1987):

- During the model experiment, the stress state within the model is subjected to redistribution either due to external force conditions, or due to the alteration of the geometrical shape of the model (excavations etc.). Changes of the stress state of the model are described by a series of tensometrical data l_i obtained at moments t_i, when $t_i < t_{i-1}$.
- If this data series of l_i does not contain a value exceeding that of the ordinate $l_{\max} = h(s_{\max})$ of the nodal point H of the last calibration loop, i.e. $l_i < l_{\max}$, this loop is used for the interpolation of all loads for the values of l_i.
- If the tensometric series includes a value of l_i that exceeds $l_{\max}$, the pertinent load s_i to this value is interpolated on the main branch of the calibration scheme. If there exist one or more entries $l_{i+1}, l_{i+2}, \ldots$, which are lower than l_i, the loads $s_{i+1}, s_{i+2}, \ldots$ are interpolated in the interpolation loop with nodal points H_i, V_i (Fig.1), while $l_{\max} = l_i$. This new loop is determined by extrapolation by means of all loops, defined by calibration measurements.
- The following two more particular rules hold true for the interpolation of loads s_i to values of l_i, which come within a certain above-mentioned interpolation loop:
  1. Load s to the value of l with the attribute of relief (-1) is interpolated on the curve, which runs through the nodal point V and the nearest (in time) point P, which has already been fixed by interpolation and whose ordinate has the attribute of surcharge $(+1)$. The interpolation leads to the determination of the point O. If the point P coincides with he nodal point H, this interpolation curve is directly the relieving branch of the loop. If this is not the case, the interpolation curve (Fig.1, weakly dashed) must be derived from the mentioned relieving branch.
  2. The load s to the value of l with the attribute $(+1)$ is interpolated on the curve, which runs through the nodal point H and the nearest (in time) point O, which has already been fixed by interpolation and whose ordinate l has the attribute of relief (-1). The interpolation leads to the determination of the point P. If the point O coincides with the point V, this interpolation curve is identical with the surcharging branch of the loop. If this is not the case, the interpolation curve (Fig.1, weakly dotted) must be derived from the mentioned surcharging branch.

These both rules are illustrated by Fig.1. In the loop H_i, V_i, three tensometric measurement are interpolated with regard to their attributes: $l_{O1}(-1)$, $l_P(+1)$, $l_{O2}(-1)$, with $l_{O1} = l_{O2}$. The interpolation to the entry l_{O1} is made directly on the relieving branch of the loop and leads to the value s_{O1}, and thus to the determination to the point O_1. For the interpolation of the load to the entry l_P, it is necessary to construct an intermediate surcharging branch, running to the nearest (in time) point with the attribute (-1), i.e. the point O_1 and the nodal point H_i. As result, the interpolation of load s_P and thus the determination of the point P are obtained. The interpolation of load to the entry l_{O2} is then effectuated on the intermediate

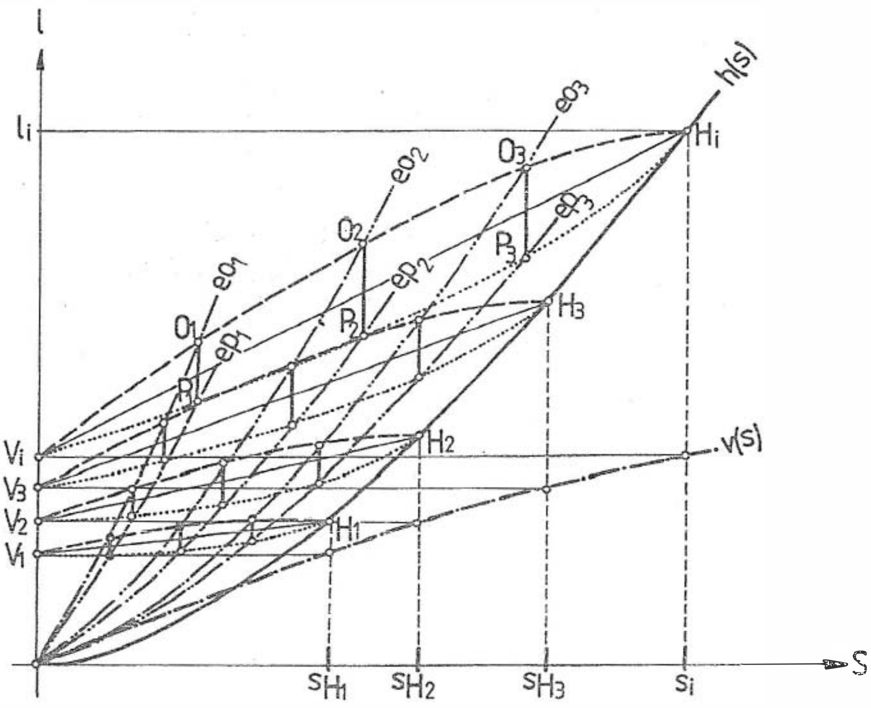

FIG 2.. Extrapolation polynoms and formation of loop

relief branch, running through the nearest (in time) point with the attribute (+1), i.e. the point P and the nodal point V_i. The interpolation enables the load s_{O2} to be determined, which is not identical with the load s_{O1} although $l_{O1} = l_{O2}$, as it is evident also from Fig.1.

3.2 Automation of the evaluation

Vencovský (1990) developed two independent but linked together computing programs for the automation of evaluation of the stress state of the SM system from tensometric data by the above described method.

The program TN1 processes the pertinent calibration data individually for each sensor. The computing results is determination of: the main and secondary branches of the calibration scheme and a system of the so-called extrapolation polynoms, which enables the above-mentioned interpolation loops to be determined in case of need. The system of these extrapolation polynoms is schematically illustrated in Fig.2. We have to do again with regression polynoms, which run through the origin of the coordinate system s, l and which adjoin the adequately chosen points on relieving and surcharging branches of the calibration loops. These points are chosen on each loop 1/4, 1/2 and 3/4 of the stress corresponding to the nodal point H of this loop.

The first triple e_{01}, e_{02}, e_{03} is used, in the program TN2, for the determination of the relief branch of a certain interpolation loop H_i, V_i in that way, that the points O_1, O_2, O_3 are computed for the abscissae 0,25 s_i, 0,5 s_i, 0,75 s_i , when s_i is the stress in the nodal point H_i. The regression polynom is then interpolated so that it runs through nodal points H_i, V_i. This polynom determines the mentioned relief branch of the loop.

The second triple of the extrapolation polynoms s_{P1}, s_{P2}, s_{P3} enables then accordingly, by means of points P_1, P_2, P_3, the surcharging branch of the studied loop to be determined. The structure of the entire interpolation loop is suggested in Fig.2, which, within the given context, may be considered an actualization of Fig.1.

Thus, the program TN2 takes over the results of the course of program TN1 and enables, individually for each sensor, the time series of stress for the time series of tensometric data to be evaluated, its alphanumerical extract to be effectuated or to be recorded in a chosen storage medium for further eventual treatment, i.g. by computing programs, developed in the past by Vencovský (1990) for continuos graphical illustration of discretely defined non-analytical two-dimensional functions.

4. Checking of the function of programs TN1 and TN2 on simple models

4.1 Model

The automatic evaluation of the stress state of physical models from the tensometric sensor data by means of the mentioned programs was checked on simple experimental models. These models were cylinder-shaped with dimensions ∅100 × 300 mm and were prepared from quartz sand with grain size 0,06 to 0,3 mm, strengthened with paraffin or epoxide resin EPOXY 1200. During construction of these models, one or two tensometric sensors were inserted in their interior, approximately in their longitudinal axis, with length spacing of about 100 mm along the axis. These were both the sensors DO14X and sensors with semiconductor pressure pickup TM440. Altogether 8 such models were prepared. They are reviewed in table 1 together with some necessary additional information.

4.2 Experiment

Models with built-in one or two sensors were left in the cylindrical metal form and inserted into an oedometer (Fig.3). Loading of the model by uniaxial uniform compression was effectuated through the lever system of the oedometer according to determined loading diagram in the way to obtain tensometric data for four calibration loops as well as for several other random chosen loading phases. An example of the loading diagram (for model No.5) is given in Tab.2.

The time interval between individual loading phases was 1 min. The data from sensors were recorded by the automatic central PEEKEL in half-minute resp. 1-minute intervals and stored in the collaborating PC-AT.

A very dense time series of measurement has been obtained, from which, however, only data from the end of every 10th minute were used. These were then processed by programs TN1 and TN2. All intermediate measurements were used only for the evaluation of the time behaviour of the model deformation and of its reaction to

TABLE 1.

model No.	composition (%) equivalent material	compression strength (MPa)	sensor S_1	sensor S_2
3	sand 97,3 paraffin 2,7	0,48	DO14X	
4	sand 97,6 paraffin 2,4	0,43	DO14X	
5	sand 97,3 paraffin 2,7	0,49	DO14X	
6	sand 97,6 epoxide 2,4	1,03	DO14X	TM440
7 8 9	sand 98,0 epoxid 2,0	0,42	DO14X	TM440
10	sand 97,8 epoxide 2,2	0,77	DO14X	

TABLE 2.

Phase	Load (kPa)	Phase	Load (kPa)	Phase	Load (kPa)
1	0,00	16	0,00	31	174,14
2	9,96	17	29,06	32	116,14
3	19,97	18	57,87	33	57,69
4	29,06	19	86,97	34	0,00
5	19,37	20	106,28	35	57,69
6	9,69	21	125,63	36	116,14
7	0,00	22	145,01	37	174,14
8	9,69	23	96,63	38	57,69
9	19,37	24	48,31	39	116,14
10	29,06	25	0,00	40	57,69
11	48,17	26	48,31	41	183,78
12	67,56	27	96,70	42	116,14
13	86,97	28	145,01	43	57,97
14	57,87	29	151,69	44	0,00
15	29,06	30	164,37		

instantaneous loading and relieving.

4.3 Results of model experiments

As it has been said, each model experiment was organized into 4 calibration loops. Graphical illustration of the loading process of a certain model (see Tab.2)

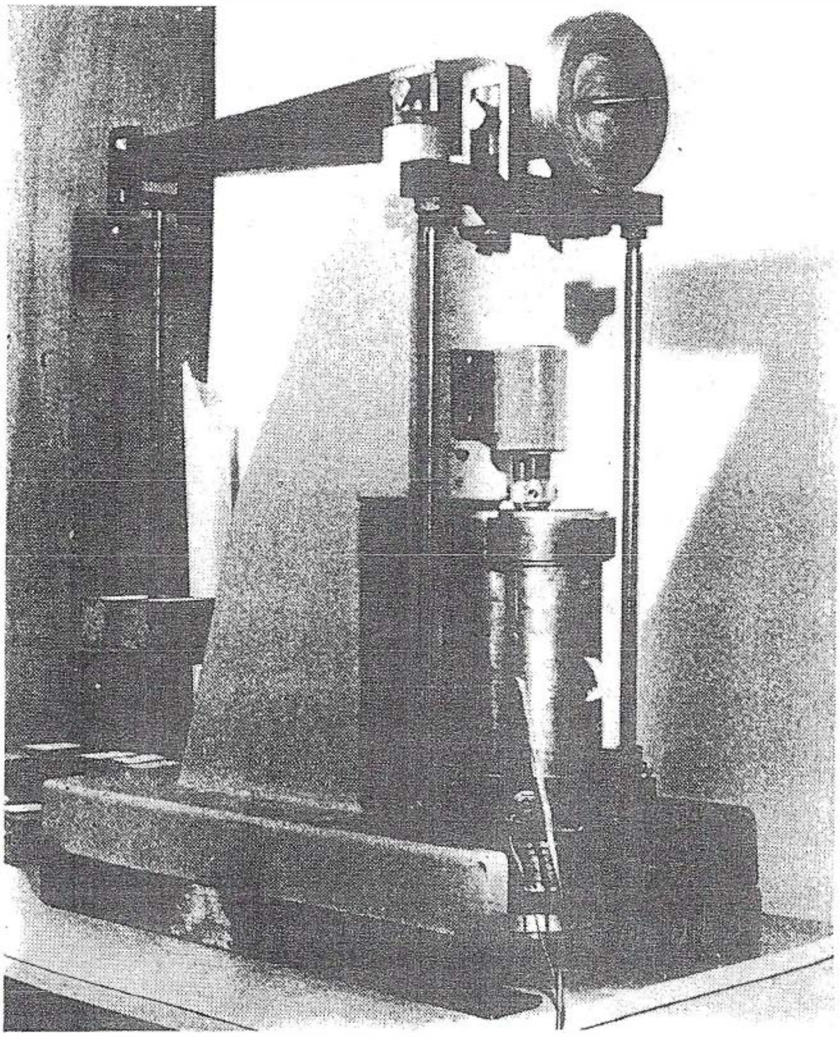

FIG 3.. Photograph of experimental model and oedometer

and corresponding tensometric data lead, for all model experiments, to almost the same result, reproduced in Fig.4 (model No.5, sensor S1). The execution of 4 calibration loops (solid lines) is evident from this Fig. together with the already mentioned after-strain of the model in time after its each instantaneous loading or relieving, illustrated by so-called consolidation curve (dotted lines).

As far as the time-dependent after-strain (additional deformation) of the model is concerned, it can be clearly seen from the figure that a completely equilibrium condition of the model could not always be established with regard to previous loading or relieving. A certain equilibrium can be stated on relieving branches, but not on the main branch. The course of the consolidation curves presumably points to the fact that the time required for establishing an equilibrium stress state in models of this kind is proportional to the value of load (phases 28, 29, 30, and higher would require a longer time for consolidation).

The processing of the calibration data by means of TN1 and TN2 programs resulted in very similar results for all above-mentioned models. For illustration, Table 3 resumes results for the model No.5.

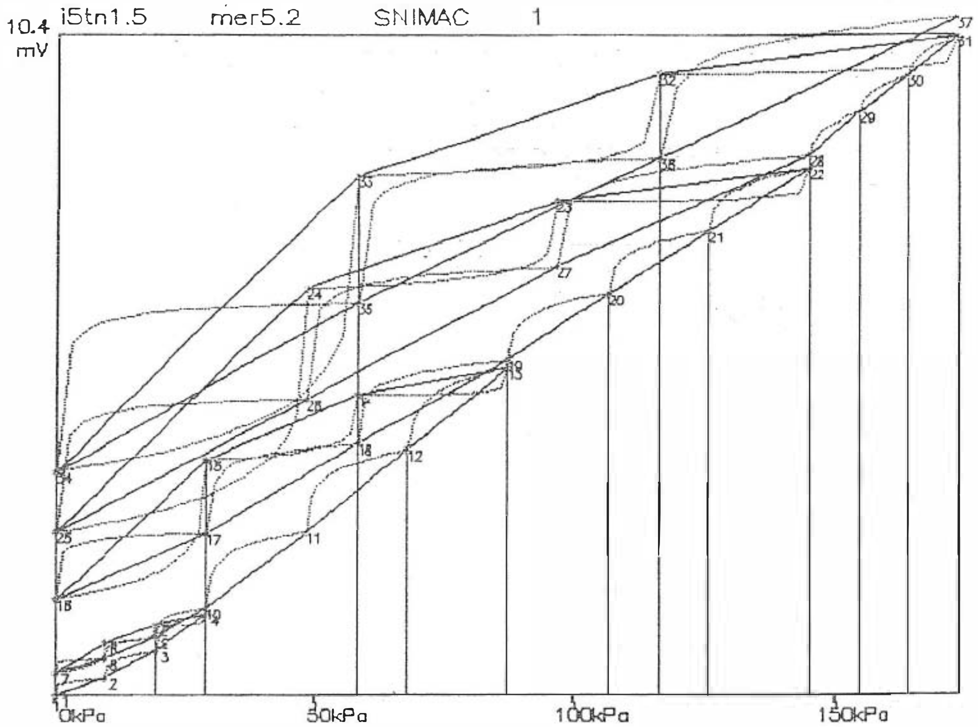

FIG 4. Illustration of the calibration measurement

It should be added to these results that the evaluation of the stress state for all model experiments has been realized in two alternatives:

I. The calibration measurement has been considered only within the range of 3 calibration loops, i.e. only till the phase 28 (see Tab.2). The stress state of the model in all higher phases was then considered unknown and therefore either extrapolated on the main branch or interpolated in loops, defined by the procedure described in chapter 3.

II. The calibration measurement has been considered within the range 4 calibration loops, i.e. it ended by the phase 37. As unknown stress phases were then considered all phases beginning by the 31st, i.e. the phase, where the 4th calibration loop originates, and stress corresponding to these phases were again determined by the above-mentioned evaluation method.

The precision resp. the effectiveness of the stress evaluation in the discussed models by the suggested automatized procedure can be defined on the basis of values of absolute and relative differences between the actual (nominal) pressures and pressures determined by evaluation. Average differences — deviations determined as quadratic mean values for individual model experiments, both types of the used sensors S1, S2 and both alternatives of calibration measurements are summarized in Tab.4.

It should be noted to the information of this Table that the so-called — rel. dev. — relative deviation is derived from the average value of nominal pressures from all evaluated phases.

Generally, somewhat better results (higher precision) could be stated for the sen-

TABLE 3.

Phase	Nominal pressure	Interpolated pressure (kPa) 3	4	Absolute difference (kPa) 3	4	Relative difference (kPa) 3	4
29	154,7	154,4		−0,2		0,0	
30	164,4	162,2		2,2		1,3	
31	174,1	170,5	156,7	−3,6	−17,4	−2,1	−10,0
32	116,1	133,9	121,6	17,7	5,4	15,2	4,6
33	58,0	61,4	53,3	3,4	−4,6	5,9	−7,9
34	0,0	0,2	0,0	0,2	0,0	0,0	0,0
35	58,0	61,2	57,1	3,2	0,9	5,5	0,7
36	116,1	120,1	115,9	4,0	−0,2	3,4	−0,2
37	174,1	174,1	174,1	0,0	0,0	0,0	0,0
38	58,0	63,3	60,6	5,4	2,7	9,3	4,6
39	116,1	119,1	117,8	3,0	2,3	2,6	1,4
40	58,0	70,3	68,0	12,3	10,0	21,2	17,4
41	183,8	184,9	185,1	1,1	1,3	0,6	0,7
42	116,1	143,2	141,8	27,1	25,7	23,3	22,1
43	58,0	70,1	67,2	12,1	9,2	20,9	15,0
44	0,0	0,3	0,2	0,3	0,2	0,0	0,0

sor type DO14X than TM440 sensors, which can be explained by higher sensitivity of former ones.

The precision of evaluated depends also on the rigidity of modelling material. The analysis of tabulated data with reference to strength data of equivalent materials for individual models (Tab.1) results in the statement that the precision of evaluation is higher for stronger materials. This information is connected with a certain theoretical, but probably not entirely correct assumption (Filip 1987), which was incorporated into the algorithm of both computing programs.

This concerns the so-called break points and the corresponding duplicating points (§ 2.3), which were supposed to be topically identical, or that their location difference was caused by incidental circumstances. This assumption apparently does not meet the fact, especially for plastic materials This can be clearly identified in graphical illustrations of all calibration measurements (Fig.4), where positions of both mentioned points display a systematical difference, whose value correlates well with the rigidity of the used material.

The incorporation of the mentioned erroneous assumption in the evaluation method explains also the paradox finding, that the precision of evaluation is either the same or lower for the alternative II, i.e. for the case of 4 calibration loops. The lower precision should rather be expected for the alternative I, in which only 3 loops are used and which should therefore be qualified for generally more labile extrapolation.

TABLE 4.

VARIANT I – 3 calibration lops

Model	Average pressure (kPa)	abs.dev. (kPa) S1	S2	rel.dev. (%) S1	S2
3	92,3	10,4	–	11,3	–
4	91,8	7,6	–	8,3	–
5	91,9	9,6	–	8,7	–
6	121,5	9,0	11,0	7,4	9,0
7	121,4	15,6	19,0	12,8	15,6
8	121,4	12,3	16,1	10,1	12,3
9	121,4	–	25,7	–	21,7
10	121,4	11,7	–	9,7	–

VARIANT II – 4 calibration lops

Model	Average pressure (kPa)	abs.dev. (kPa) S1	S2	rel.dev. (%) S1	S2
3	92,3	7,8	–	8,4	–
4	91,8	13,1	–	14,2	–
5	91,9	9,3	–	10,1	–
6	121,5	8,8	19,0	7,3	15,7
7	121,4	27,4	23,4	22,8	19,3
8	121,4	14,8	12,9	12,2	10,6
9	121,4	–	22,1	–	18,2
10	121,4	11,6	–	9,5	–

5. CONCLUSIONS

The discussed results prove clearly the overall functionality of both the suggested method and the software tools, developed in the modelling department of the Institute of Geotechnics (Czech Acad.Sci.) for processing the tensometric measurements of the stress state of physical rock problem models in conditions of the quoted laboratories. Precision of stress state determinations varies actually around 10% and is hitherto limited partly by the not entirely perfect theoretical formulation of the evaluation procedure, partly by the stress-strain properties of the modelling materials used. Higher precision can be expected for stronger materials. The precision of evaluation may further be increased by further modifications of both computing programs TN1 and TN2 with regard to experimental information about the behaviour of the system sensor-modelling material. Nevertheless, the established 10% precision is, for the meantime, entirely acceptable, especially when considering the fact that the evaluation of the stress state of pressurized physic rock mass models depended, until recently, on manual procedures according to insufficiently clear conceptions.

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Určení napjatosti fyzikálního modelu horninového masivu pomocí tenzometrických snímačů

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Určování napjatosti fyzikálního modelu horninového masivu pomocí tenzometrického měření bylo jedním z dlouhodobých témat výzkumné práce oddělení modelování ÚSMH AV ČR. V současné době dospěl vývoj této problematiky k těmto výsledkům. Jsou k dispozici kvalitní, spolehlivé a rozměrově přijatelné tenzometrické snímače, pracující ve spojení s automatickou ústřednou PEEKEL, umožňující registraci tenzometrických údajů až 400 snímačů. Pro zpracování těchto údajů a automatizované vyhodnocení napjatosti fyzikálního modelu v okolí každého snímače byly vypracovány dva na sebe navazující výpočetní programy. Funkčnost těchto programů byla testována pomocí modelových zkoušek. Získané poznatky potvrzují možnost rutinního užití obou programů, jakož i jejich vyhovující schopnosti extrapolovat hodnoty napětí, které leží již mimo oblast provedeného cejchování.