ACTA MONTANA IGt CSAS (1992)
Series A, No. 1(87), 57—68

EXPERIENCE IN MODELLING A PARTICULAR HYDROGEOLOGICAL PROBLEM ON A THREE-DIMENSIONAL PHYSICAL MODEL

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Abstract: A physical 3-D model was used to determine deformations of a surface-mined coal seam endangered by the overpressure of artesian groundwater. The modelling relations were derived by dimensional analysis, after considerable simplification of the problem. The equipment for modelling and construction of the model are described and the method of measuring deformations on the model is presented. The values of the model deformations were compared with the solution of the stability of the open-pit mine bottom by means of FEM and with the data measured in an open-pit mine by very precise levelling.

Key words: geotechnics; stability of rock mass; physical model; open-pit mine; overpressure of underground water; measuring of deformations

1. INTRODUCTION

For many years, methods of modelling of processes on physical models have been used to study various problems of rock mechanics associated with the extraction of mineral raw materials and with the construction of underground objects. The papers by Kuznetsov *et al.* (1959) and Goodman (1976) are classical examples. Of the recent papers those of Barton (1979), Stimpson (1981), Müller (1980) can be referred to. They deal with the application of physical modelling methods in geotechnics. In Czechoslovakia, Kožešník (1983) was concerned with research into and development of the theory of similarity and the modelling. Kohoutek (1961) studied practical application of this method to problems in geotechnics.

Mathematical modelling methods, above all the finite element method, have become to be used more frequently with the development of computers. Nevertheless, many problems can also be studied simultaneously on 3-D models to an advantage. The results obtained by the two methods can then be compared.

The reliability of the results obtained both from mathematical and physical models depends on the knowledge of the actual behaviour of the rock mass. Because of insufficient information and since it is impossible to obtain all the necessary data, not all factors involved can be included. Consequently, the relevant parameters, which predominantly affect the relationship between the model and reality, must be found in solving each particular problem.

In studying a particular problem on a model, six basic stages of solution are distinguished:

1. Formulation of the problem.
2. Construction of the model.
3. Solution of the problem on the model.
4. Analysis of the model solution.
5. Correlation between the results obtained on the model and the data measured in situ.
6. Realization of these results.

2. FORMULATION OF THE PROBLEM

The purpose of the model experiments was to determine the vertical deformations of the bottom of an open-pit mine caused by the overpressure of artesian, thermal, gas-bearing waters. In open-pit mining of brown coal, impermeable tuffitic layers are temporarily exposed at the open-pit mine bottom. The artesian roof of the gas-bearing thermal waters is formed by the base of these layers. The delivery level of the waters is above the extracted coal seam (Fig. 1). The uplift pressure of artesian waters is counteracted by the weight, shape and strength of the rocks forming the tuffitic plate.

2.1. Principles of modelling

The modelling of processes taking place in a rock mass is based on the relationships derived from geometrical and physical similarity. To determine the values of vertical displacements at the exposed open-pit bottom due to overpressure of artesian waters, the following relevant quantities were taken into consideration:

- mass density ϱ,
- uncovered overpressure of artesian waters p,
- gravity g,
- cohesion c,
- time t,
- vertical deformation u,
- angle of internal friction ϕ.

The impacts of other factors affecting processes in the rock mass were assumed to be less important. Hence the simplification of the model.

The following dimensional equation, which is a function of the relevant factors,

$$f(p,\ \varrho,\ g,\ c,\ t,\ u,\ \phi) = 0$$

describes the behaviour of the rock mass in a simplified form given by the choice of these factors. According to Buckingham's theorem, as presented, e.g., by Stillborg *et al.* (1979), a set of dimensionless parameters, which are functions of the dimensional equation, can be found. In the relationship between the model and reality, the corresponding parameters are equal.

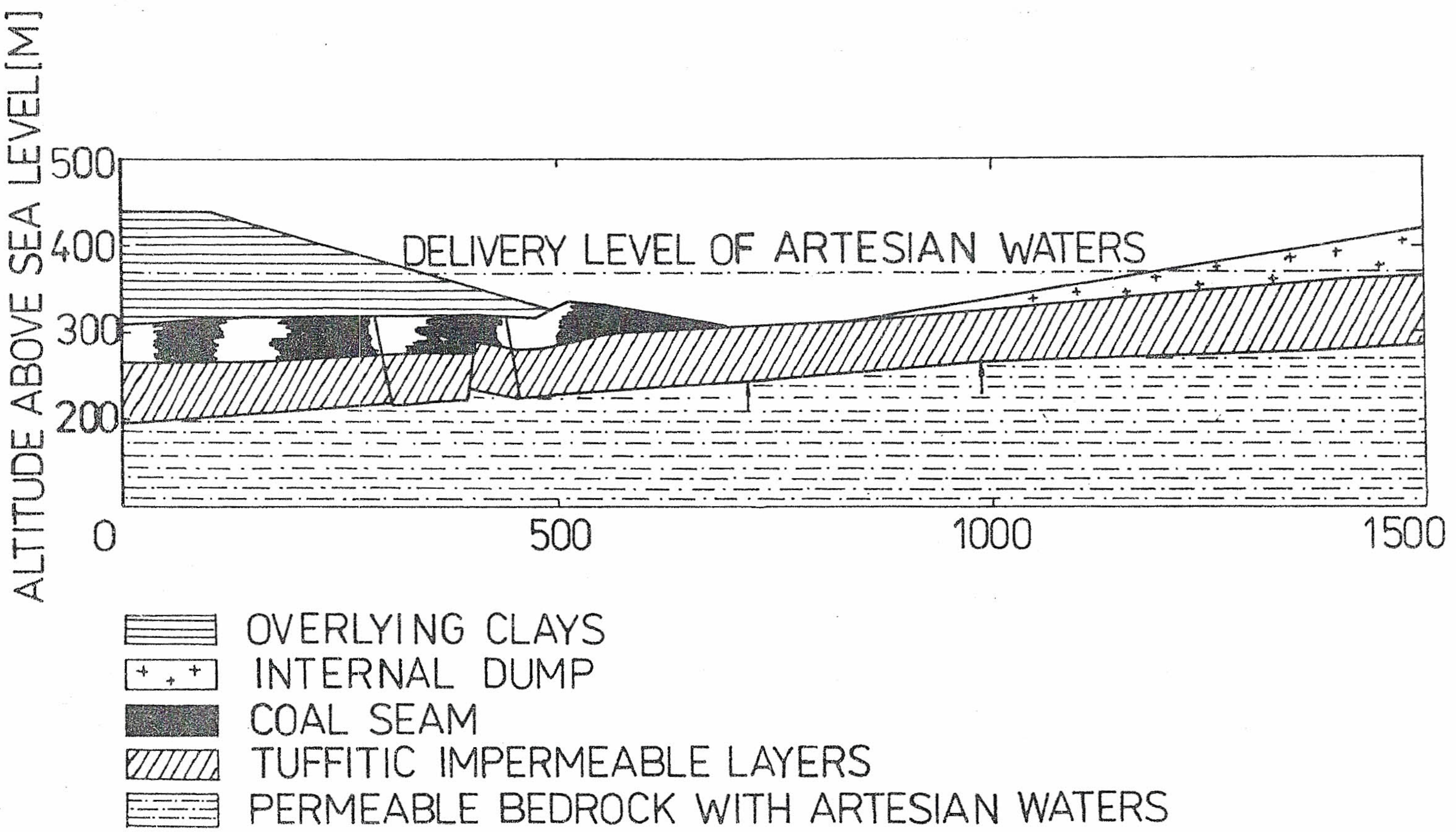

Fig. 1. Vertical section of the model for the state of extraction in 1987.

The dimensionless parameters are determined from a system of equations in relevant variables and corresponding basic units: L (length), T (time) and M (mass).

	ϱ	p	g	c	t	u
L	–3	–1	1	–2	0	1
T	0	–2	–2	0	1	0
M	1	1	0	1	0	0

The number of dimensionless parameters is equal to the total number of relevant variables (6) minus the rank of the dimensional matrix (3).

In our case three dimensionless parameters Π_1, Π_2, Π_3 were determined. The unknown exponents of the six relevant variables were derived from the system of three linear equations by making three independent choices of the remaining three exponents x_4, x_5, x_6:

$$\begin{bmatrix} -3 & -1 & 1 \\ 0 & -2 & -2 \\ 1 & 1 & 0 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} = (-1) \begin{bmatrix} -2 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{Bmatrix} x_4 \\ x_5 \\ x_6 \end{Bmatrix}$$

The following three dimensionless parameters were obtained:

$$\Pi_1 = \frac{gc}{p}, \quad \Pi_2 = gt\sqrt{\frac{\varrho}{p}}, \quad \Pi_3 = \frac{\varrho u}{c}$$

The fourth dimensionless parameter was the angle of internal friction ϕ. The phenomenon under study was described by these parameters in an acceptable simplification.

Geometrical similarity of geological layers, shapes and positions of geological dislocations and planimetric features of the open-pit mine bottom was preserved throughout the entire model. The sections of the overburden and faces of the internal dump were simplified in dependence on the scale of the model, i.e. 1 : 500, adopted also with regard to the modelling equipment available and the necessity of simulating an extensive area.

3. CONSTRUCTION OF THE MODEL

3.1. Laboratory tests of crucial parameters of equivalent materials

Equivalent materials were prepared with a view to working with the relevant factors; consequently, laboratory tests were concentrated on determining the volume weight and the shearing strength given by cohesion and the angle of internal friction. The properties of the equivalent materials were examined by laboratory methods usual in soil mechanics. The shear box test and standard triaxial test were used.

The equivalent material should also satisfy other criteria. The equivalent material should exhibit the same character of failure as the rock mass. Moreover, it should be easy to mix so that it may be deposited conveniently in the model.

Mixtures of sand or balottine and/or gravel, slack coal and ferrosilicon were used to prepare the equivalent material. To obtain the required properties, binders were added.

3.2. Modelling equipment

A modelling stand with base dimensions of 1430 mm × 3500 mm and wall height of 800 mm was used for the construction of the model. The steel frame of the stand was secured against undesirable deflections. Water flowed into the model through openings made in the base of the modelling stand via an overspill device whose vertical displacement controlled the height of free water level (Fig. 2.).

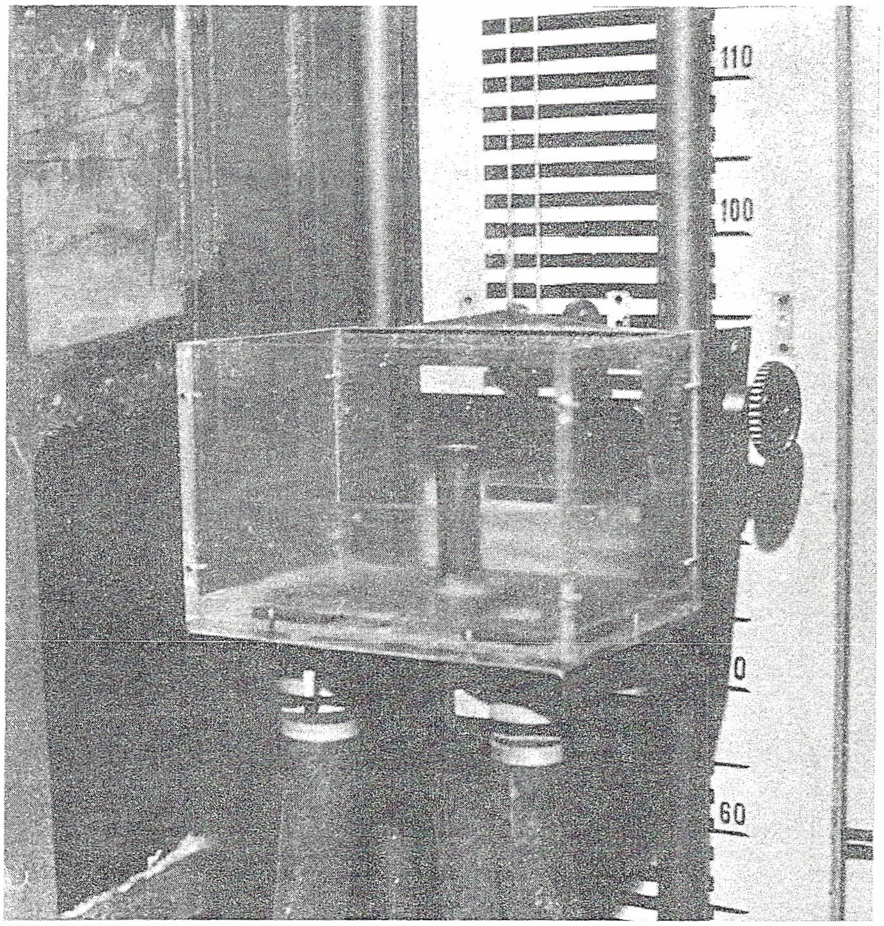

Fig. 2. The overspill for controlling the height of water level.

3.3. Construction of models

The model was constructed using basic geological documents containing information on:

- isolines of the geological series of strata,
- geological dislocation,
- planimetric and elevation features of the overburden and internal dump,
- sections and situation plan of the open-pit mine bottom.

The model was constructed by means of templets shaped according to the isolines of the boundaries of various geological layers and isolines of the surface of the modelled area.

The equivalent materials were deposited in the modelling stand and their surfaces were shaped and compacted. A fine polybutadiene membrane separating the permeable bedrock from the layers of impermeable tuffitic clays, which formed the artesian roof of the gas-bearing thermal water, was laid on the modelled bedrock so that it did not restrict the deformations of the impermeable bedrock.

4. SOLUTION OF THE PROBLEM ON THE MODEL

4.1. Measurement of deformations on the model

The model experiment consisted in gradually extracting the equivalents of the overburden and coal seam, and dumping the internal waste dump analogously to the actual progress of extraction in the open-pit mine. During the model experiment, the water level in the model corresponded to the height of the free water level in the open-pit mine.

Since the surface of the model was changed continuously (see Fig. 3), the deformations of the coal seam bedrock were measured trigonometrically. For this purpose, during the construction of the model, the equivalent of a drainage adit was placed on the surface of the impermeable layer modelled. This adit consisted of segments of a plastic tube. Measuring marks were placed in it (see Fig. 4), each being connected with a light. A theodolite was positioned in front of an opening cut in the wall of the modelling stand, along the axis of the adit. The vertical angles at the measuring marks were measured after each change of deformational conditions in the model. The measuring marks made it possible to obtain four independent readings of the measured angles, which improved the accuracy of the method. The vectors of displacement of the measuring marks, and, thus also deformations of the model in this direction, were determined using the known distances of the theodolite axis from the measuring marks and measured changes of vertical angles. Relative to the initial position, the vertical displacement d_z for the n-th stage and i-th measuring mark can be expressed as:

$$d_{z\,in} = a_i \operatorname{tg}(\alpha_{in} - \alpha_{01})$$

where α_{in} is the vertical angle measured at the n-th stage, α_{01} is the vertical angle measured at the beginning of the model experiment, and a_i is the distance of the measuring mark from the theodolite axis.

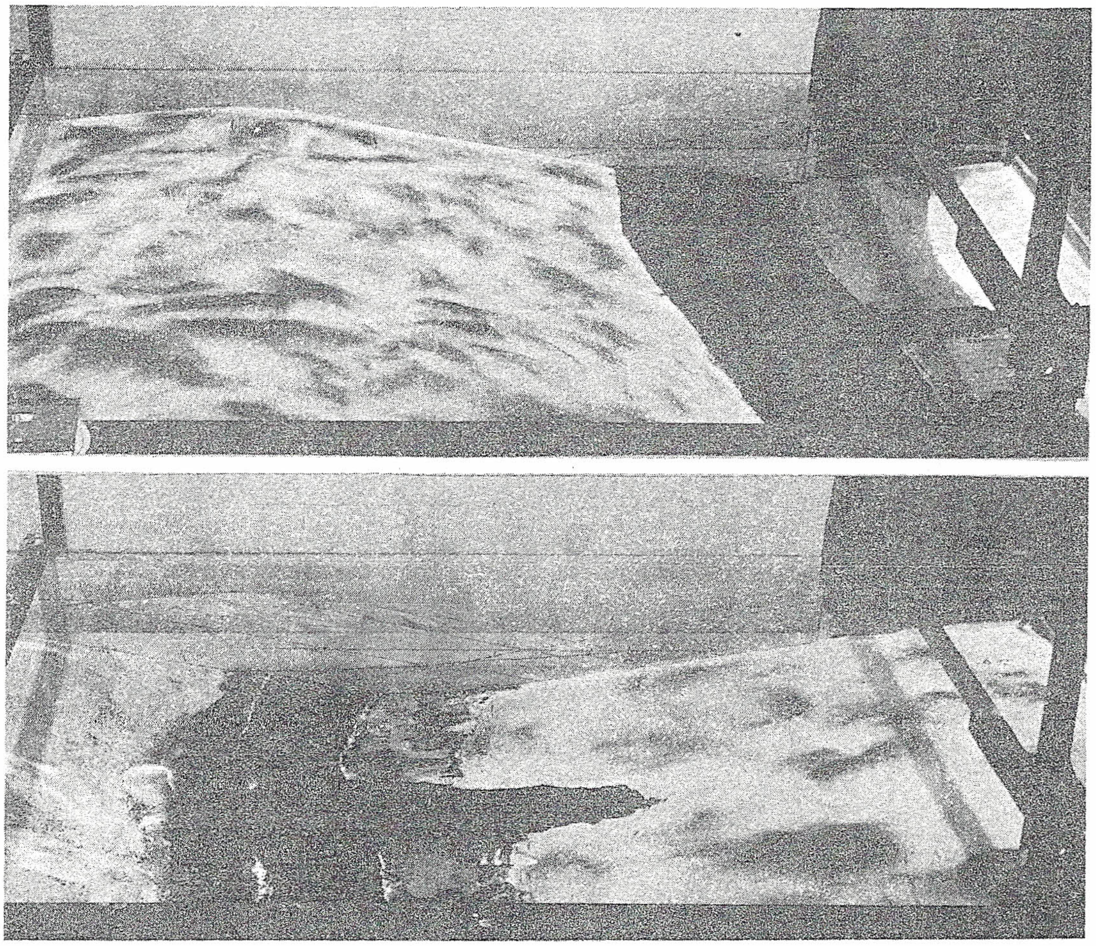

Fig. 3. Model surface before starting the experiment and for the state of extraction in 1987.

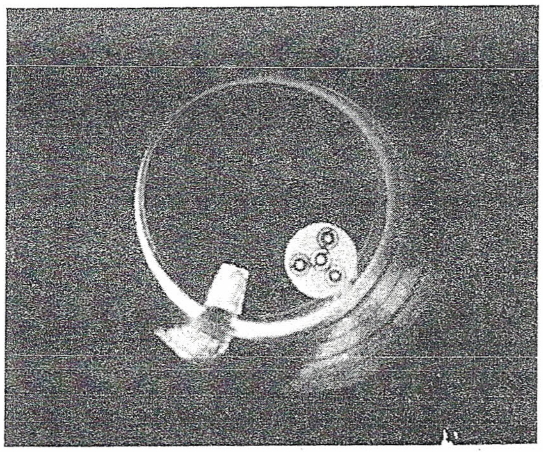

Fig. 4. Illuminated measuring mark situated in the equivalent of mine adit.

4.2. Results of the model experiment

During the model experiment, the vertical angles at the measuring marks were measured after each change in the conditions in the model. The values of vertical displacements of the measuring marks, calculated from these measurements, yielded the deformation of the coal seam bedrock for various conditions given by the progress of the mining.

Fig. 5 shows the vertical displacements of four selected measuring marks of a model, on which the deformations of the coal seam bedrock between 1980 and 1990 were determined. The model experiment was carried out in 1985. The results of this model experiment were to indicate whether steps should be taken to reduce the deformations at the mine bottom. No steps were proposed since the model measurements showed that the maximum deformations at the mine bottom would not exceed 300 mm (see Fig. 6).

The same problem was simultaneously studied on a mathematical model by means of the FEM method. The mathematical model used the same geological documents and the same actual properties of rock mass as the physical model (Doležalová, 1985). Good agreement between the values of the maximum deformations of the mine bottom, obtained by both methods of modelling, is evident from Figs. 6 and 7.

Since 1984 the deformation of the bedrock of the coal seam has been monitored continuously by levelling measurements. The measurements are made using the system of measuring marks, placed in the drainage adit. It has now become possible to compare the deformations predicted by the model experiment with the actual displacements recorded in the open-pit mine.

Fig. 8 presents a graphical comparison of the values of deformations, determined at the three points of the whole system of levelling points whose location in the drainage adit corresponds to the measuring marks in the model. The differences between the values of deformations measured in the open-pit mine and those determined earlier by the modelling experiment are not significant enough to exclude application of modelling methods. With regard to the good agreement of both model solutions, the differences in deformations can be assumed to have resulted from incorrectly introduced input parameters for modelling. The incorrect properties of the rock mass and the planned progress of mining (shape of the mine bottom, gradient of slope of the overburden and internal dump, etc.). were reflected here. In spite of these deficiencies the results of the model experiment can be used for long-range forecasting of deformations of the mine bottom.

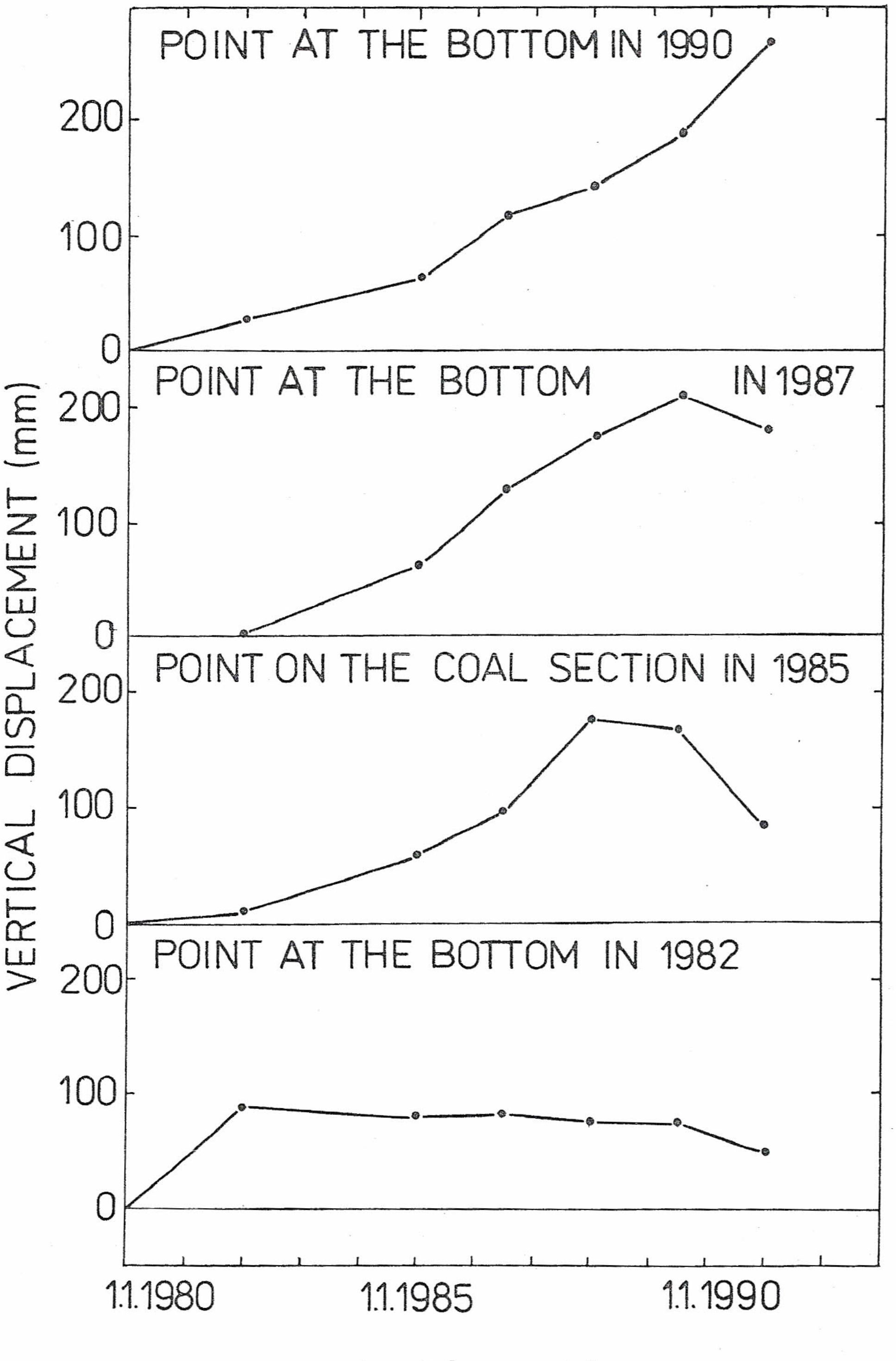

Fig. 5. Vertical displacements of measuring marks measured during the model experiment.

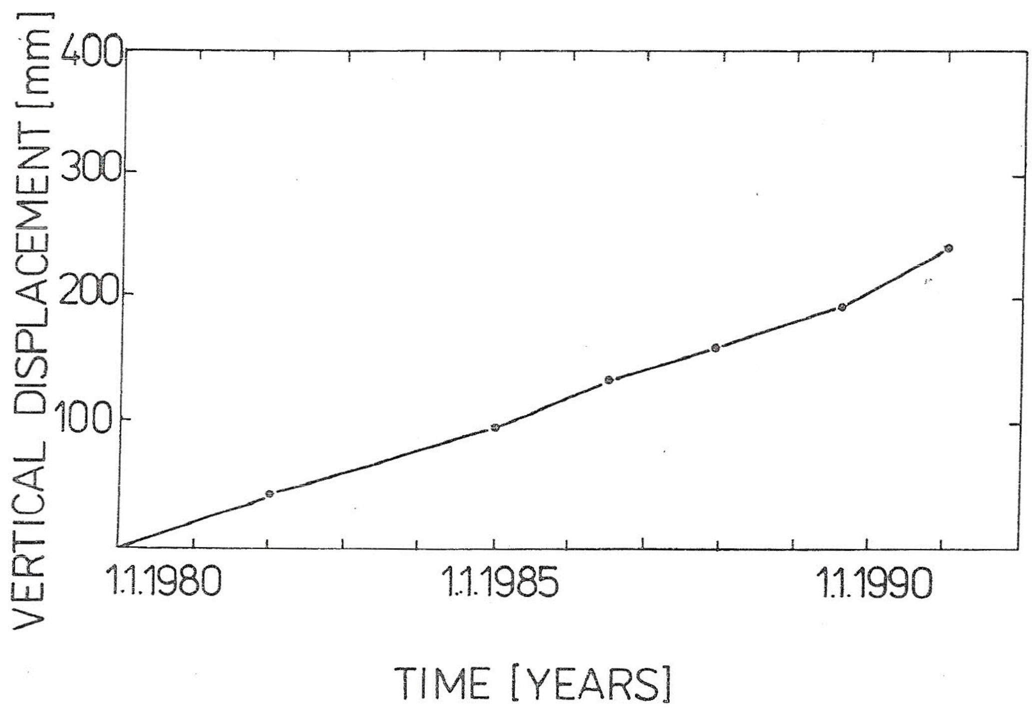

Fig. 6. Maximum vertical deformations of the mine bottom determined in the three-dimensional physical model.

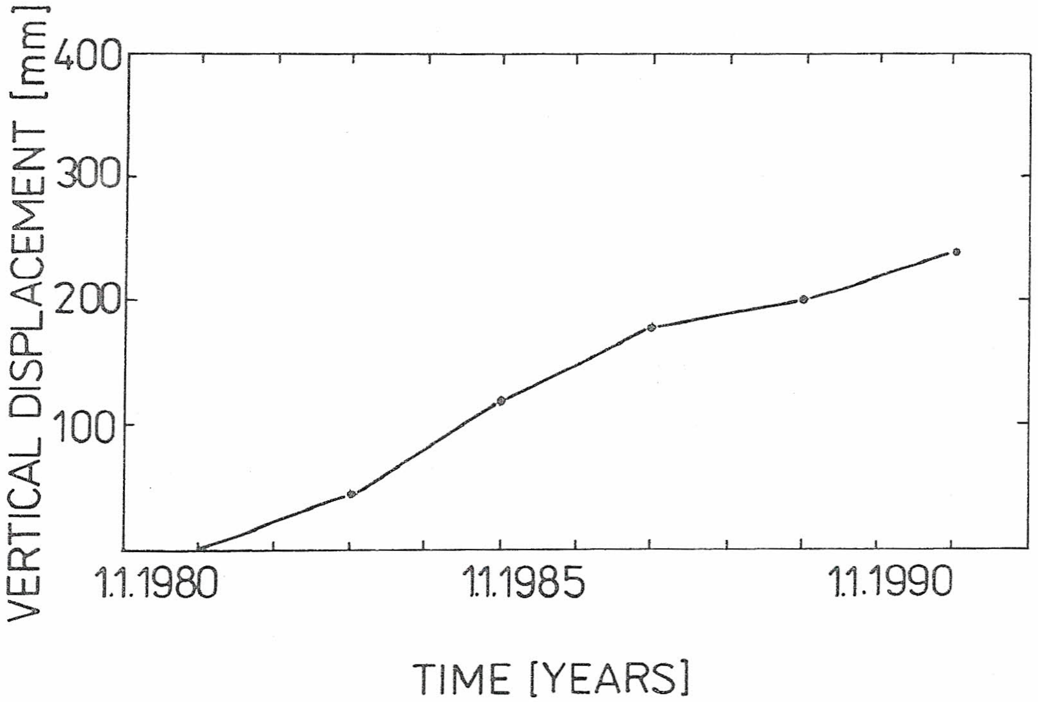

Fig. 7. Distribution of maximum vertical displacement of the mine bottom solved by the finite element method.

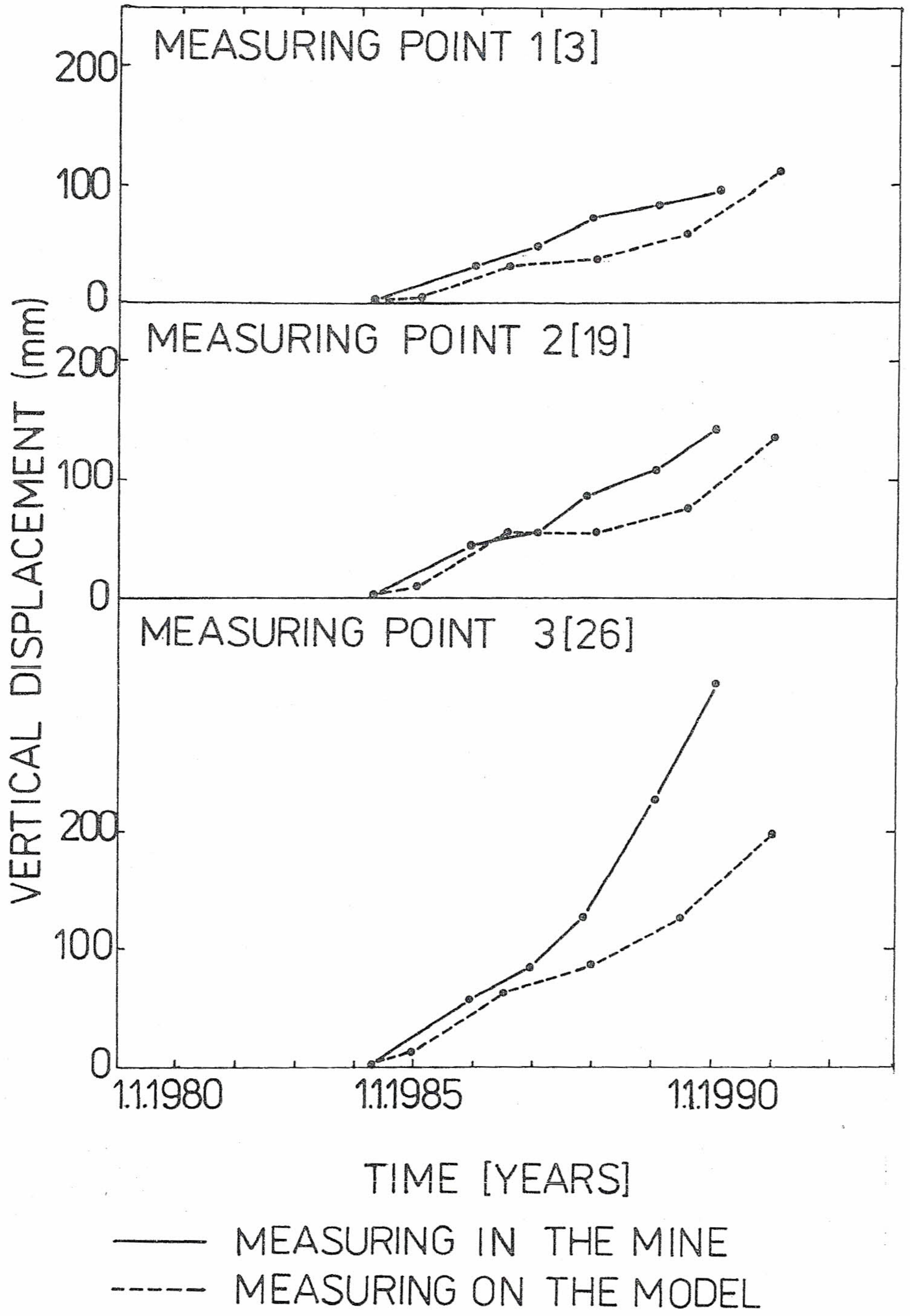

Fig. 8. Comparison of levelling values and displacements determined in the model experiment.

REFERENCES

Barton N.R. (1979). Model studies of very large underground openings at shallow depth, in *Proceedings Fourth Congress of the International Society for Rock Mechanics* **1**, Balkema, Rotterdam, 583–590.

Doležalová, M. (1985). Opencast mine Jiří II. Stability solution of the mine bottom by the finite element method, Hydroprojekt, Prague (in Czech).

Goodman, R.E. (1976). *Methods of Geological Engineering*, West Publishing Comp., San Francisco.

Kohoutek, J. (1961). Conditions of physical similarity in solving problems of rock mathematics on models, in *Sborník prací Hornického ústavu ČSAV*, Vol. 4, Prague (in Czech).

Kožešník, J. (1983). *Theory of Similarity and Modelling*, Academia, Prague, 213 pp. (in Czech).

Kuznetsov, G .N., M.N. Bud'ko, A.A. Filippova, and M.F. Shklyarskiy (1959). *Study of rock pressure on models*, Ugletekhizdat, Moscow (in Russian).

Müller, L. (1980). Sinn und Berechtigung von Modellversuchen in der Geomechanikforschung, *Rock Mech.* **13**, 39–52.

Skořepová, J. (1992). Demonstrations of creep on three-dimensional physical models, *Acta Montana* 84, 193–202.

Stillborg B., O. Stephason and G. Swean (1979). Three-dimensional physical model technology applicable to the scaling of underground structures, in *Proceedings, Fourth Congress of the International Society for Rock Mechanics* **2**, Balkema, Rotterdam, 655–662.

Stimpson, B. (1981). Laboratory techniques for demonstrating rock mass behaviour, *Int. J. Rock Mech. Min. Sci. and Geomech. Abstr.* **18**, XII, No. 6, 535–537.

ZKUŠENOST S MODELOVÁNÍM KONKRÉTNÍHO HYDROEOLOGICKÉHO PROBLÉMU NA PROSTOROVÉM FYZIKÁLNÍM MODELU

Jiřina Skořepová

Prostorový fyzikální model byl využit ke stanovení deformace podloží povrchově těžené uhelné sloje namáhané vztlakem podzemních artéských vod. Vztahy pro modelování byly odvozeny při značném zjednodušení problému na základě dimensionální analýzy. Je popsáno zařízení pro modelování a konstrukce modelu. Rovněž je uveden způsob měření deformací na modelu. Hodnoty deformací určené na fyzikálním modelu byly konfrontovány s řešením stability dna lomu metodou konečných prvků a s údaji naměřenými na lomu metodou velmi přesné nivelace.

Received 5 September 1991