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ASSESSMENT OF SURFACE DEFORMATION DUE TO UNDERMINING

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INTRODUCTION

The observation of effects of undermining on the surface in the area of the Kladno district has been carried out within the long–term perspective. Basing on periodical measurements of subsidence of buildings (carried out already since 1895), repeated measurements of the official levelling (since 1945) and later on detailed periodical measurements of the local levelling network (since 1957), some relations for the effect of mining on the deformation of surface have been derived [Zámek, 1979]. These long–term observations in the Kladno area resulted, above all, in the determination of the angle of draw (effect of mining on the surface). This angle is defined as the angle included by the connecting line of the working face edge and the site of surface, where the subsidence due to mining equals a small chosen value, with the horizontal plane [Ženč, 1967]. Angle of draw depends on the physico–mechanical properties of overlying rocks, on tectonic structure dip of the deposit and, last but not least,on the mining method. Its value is therefore not constant within all parts of the Kladno area, but it varies within the range from 65° in sites without expressive tectonics, through 58° for heavily faulted areas, down to 55° sites where multiple undermining of the area took place [Lucák, 1968].

Long–term observation enabled also the time distribution phenomena on the surface to be determined. It has been shown that 70 % of the value of maximum subsidence will be felt, on the surface, within three years, and the complete dieing–out of the subsidence takes place within the following 2–4 years.

For an evaluation of mining effects on surface structures, the preliminary values of subsidences and the shape of the subsidence basin, which is formed due to undermining, should be known. Various computing methods are used to this purpose, in Kladno district above all the most simple Bals method of preliminary calculation of subsidence from the formula

$$s = m.a.z.e \quad ,$$

where

$s =$ total assumed subsidence of a point of the surface,

$m =$ thickness of the coal seam,
$a =$ coefficient of mining,
$z =$ time factor,
$e =$ factor of effectiveness, which expresses the ratio of the extracted area to the full effective area.

Using this calculation for horizontally deposited seams, it is possible to attain the mean calculation error of preliminary subsidence of 15 – 20 % of the total subsidence, or, at very favourable conditions, even better [Havlík, 1967].

For a more complex examination of the deformation extent on the surface of the undermined area during the extraction of the shaft pillar of the mine Mayrau, an experimental method has been used in addition to mathematical methods. A three–dimensional physical model from equivalent materials has been chosen for this experimental study.

PHYSICAL MODELLING IN GEOMECHANICS

Modelling of effects occurring within the rock mass affected by anthropogenic activities, on physical models, has been used for many years [Kuznecov, 1959]. This method has been used for solution of various geotechnical problems connected with underground and open–pit mining, with construction of subsurface structures and many other purposes. Very good results were obtained, e.g., in the prediction of the deformation of bottom of an open–pit coal mine strained by uncovered overpressure of artesian water [Skořepová, 1992].

Laws of physical and geometric similarity are used as basis for the formation of modelling conditions. Dimensional equation, which describes the behaviour of the rock mass, may be reduced, basing on the dimensional analysis [Kožešník, 1983], for the relation between the reality and the model, to the problem of finding the relevant non–dimensional parameters. There are a function of that equation and are numerically equal for both the model and reality. The geometrical similarity results in the proportionality of dimensions and equality of angles.

CONSTRUCTION OF THE MODEL OF THE SHAFT PILLAR AREA

Generally, the 3–D model represents the area of interest reduced in a suitable scale. With consideration for the deposition depth of the excavated coal seam – about 500 m below surface [Živor, 1994], the necessity to represent a relatively large territory of the assumed subsidence basin, in view of the size of the available modelling stand and technical possibilities of modelling, the scale of 1:750 was used for this model.

The model was constructed in a stand with dimensions 143,5 × 128 × 80 cm (length × width × height) and represented, due to the chosen scale, the territory of 1076 × 960 m area.

The rock medium was substituted, in the model, by model materials, whose decisive physical and mechanical properties corresponded with properties of rocks of the Kladno basin [Polák, 1963; Albert, 1992]. Owing the small size of the model, it was very difficult to attain the required properties. Emphasis was laid, above all, to the attainment of equality of the limiting angle effect, which was established, basing upon long-term levelling measurements within the modelled area (which belongs to less tectonically affected ones), to 65° [Lucák, 1968]. Mixtures of sand of various grain size (from 0,2 to 2,0 m), plaster, mica and paraffin were used for the preparation of modelling materials.

Information available for the construction of model involved geological data, including a vertical section through the modelled territory drawn through the shaft Mayrau within the direction of dip of the coal seam and information on tectonic dislocations within the shaft pillar zone [Brož, 1993]. Further, available were also data concerning the planimetric and altimetric situation of the surface and mine maps containing data on exhausted areas and planned mining progress within the shaft pillar during the years 1993 – 2000.

The small scale of physical model was a reason for substantial generalization of modelled facts. Care was taken to observe, as precisely as possible, the geometrical similarity of the model and reality.

For the simulation of the exploitation within the shaft pillar in the model, an entirely untraditional method of successive de-melting of paraffin blocks was used. The dimensions of blocks, in the model scale, corresponded with those parts of the coal seam, which should be extracted from the mine during the years to come. The seam thickness was assumed to be 8 m. The structure of the model was adapted to method of de-melting of paraffin blocks.

The bedrock of the mined seam, whose physical properties do not particularly affect the deformation process, was made, in the model, from plaster block within 6° dip to the north, corresponding with the general dip of the coal seam. Under parts of the shaft pillar, which were subjected to mining, a 3 cm deep deaerated cavity was left in the model. On the backing thus prepared, a perforated model sheet was placed, to the back side of which heating elements (Fig. 1) were fixed, copying the shape of individual blocks, together with adjustable braces for preventing of deflection of construction. Fig. 2 illustrates the placing of paraffin blocks, their separation and covering with an Al-foil, which prevented the falling of the modelling material, which substituted (in the model) the overlying rocks, into the space under the perforated sheet. The cavity was designed for holding – of the molten paraffin. The arrangement of the entire device can be seen on the section through the stope in the model (Fig. 3).

The hanging wall of the coal seam, consisting mainly of layers of sandstones and claystone of varying thickness [Živor, 1994] was generalized, in the model, in the way to preserve their mutual ratio (approximately 2:1).

The modelled territory is traversed by two significant tectonic faults. The Mayrau fault intersects the shaft pillar on the south-west and its slip is about 8 m. Owing to the model's scale and ignorance of the spatial shape, this fault could not be modelled with sufficient precision. On the north-east of the shaft pillar, a significant fault dipping with the angle of draw with 120 m slip is situated. This fault is composed from several different floes (Fig. 4) [Michálek, 1972]. In the model, it was substituted by a single curved surface (Fig. 5).

The surface of the model was shaped by means of sections A–A' to F–F' drawn

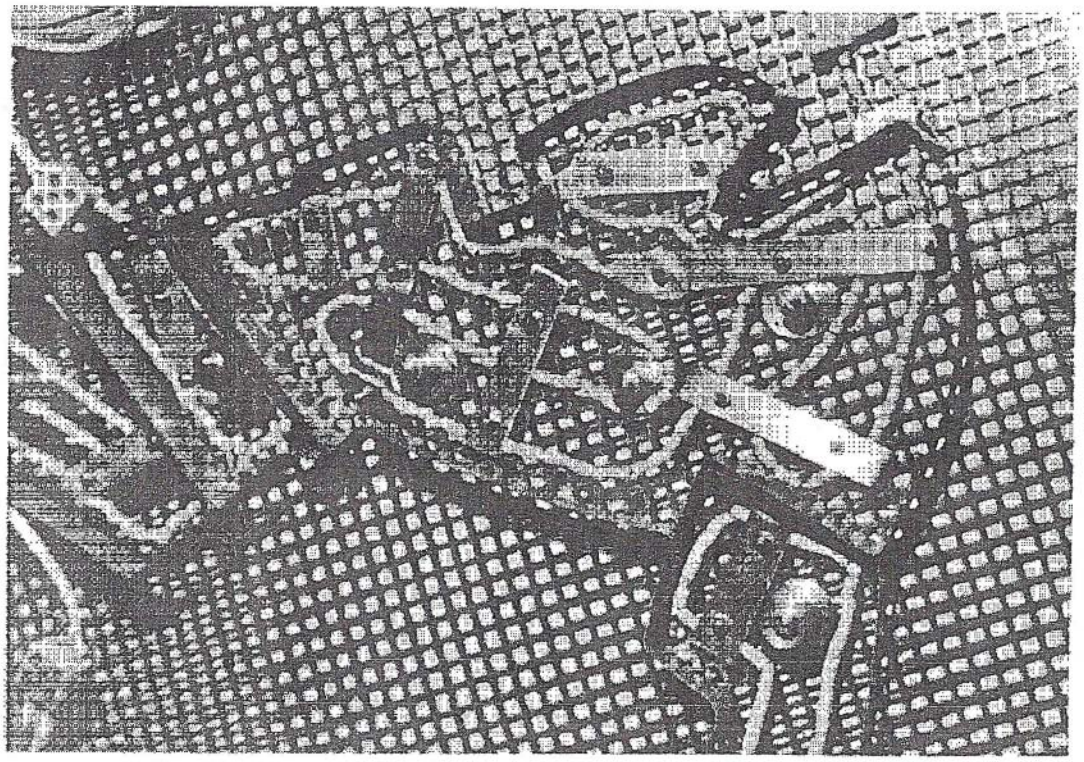

FIG. 1. Heating elements (view from below)

on the basis of isolines of the surface of the modelled territory (Fig. 6).

The analytical stereophotogrammetric method [Vencovský, 1989] was used to determine surface deformation. This method enables the digital spatial coordinates of any point, suitably marked on the model's surface, to be derived at an arbitrary chosen moment of the deformation process. To that purpose, two simultaneous survey photographs (left and right) are taken at chosen model experiment phases, by two photo–cameras situated on the stereo–basis. The method requires a stationary spatial field of photogrammetric control points (minimum 6 points) to be determined, whose pictures are clearly visible on both the left and right photograph of stereo–couple. Analytical processing of data obtained by measurement of pictures by means of the field of control points is used to determine changes of coordinates of points on the model surface compared with the initial position.

The precision of the stereophotogrammetric method in determination of coordinates in the vertical direction and in the direction perpendicular to the axis of shot is 0,1 – 0,2 mm. The average error in the shot direction of take is 2 – 2,5 – times higher. This means, for the scale of 1:750, that vertical displacements of the model surface are determined, from survey pictures, with an error of 7,5 – 15 cm.

For a perfect orientation at measurements of stereo–couples of photographs, the model surface was covered with squared network and bestrewn with sings of detailed points (Fig. 7).

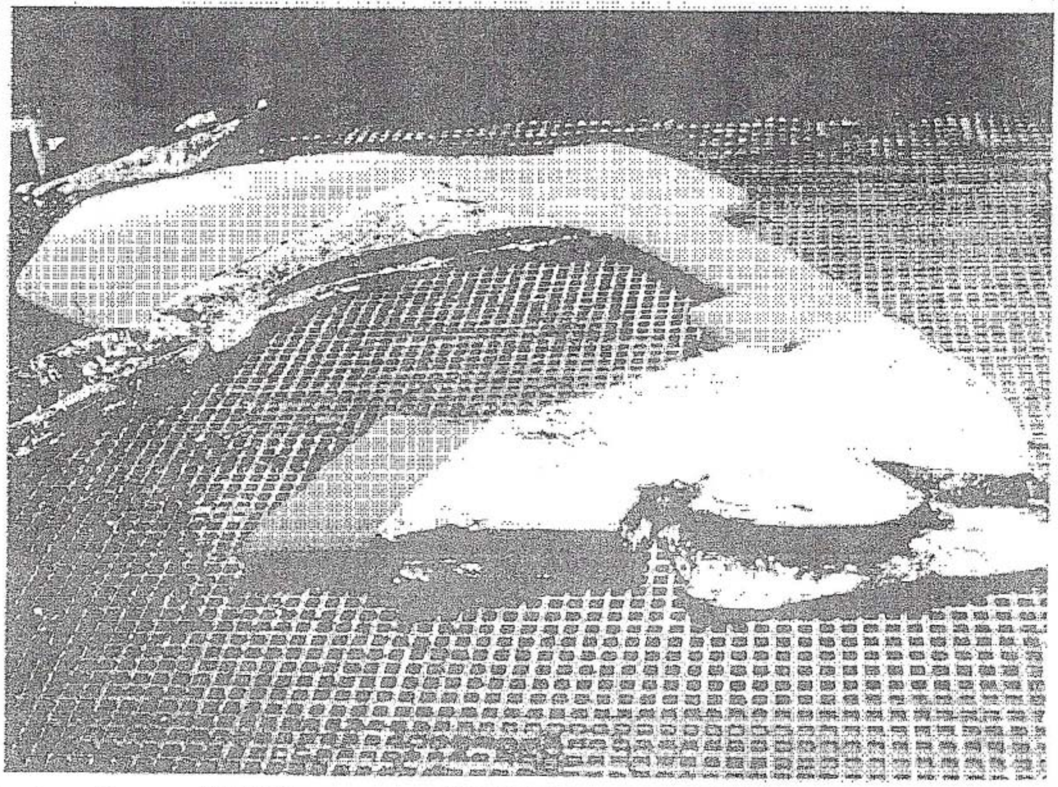

FIG. 2. Paraffin block simulating the exploited coal seam within the model

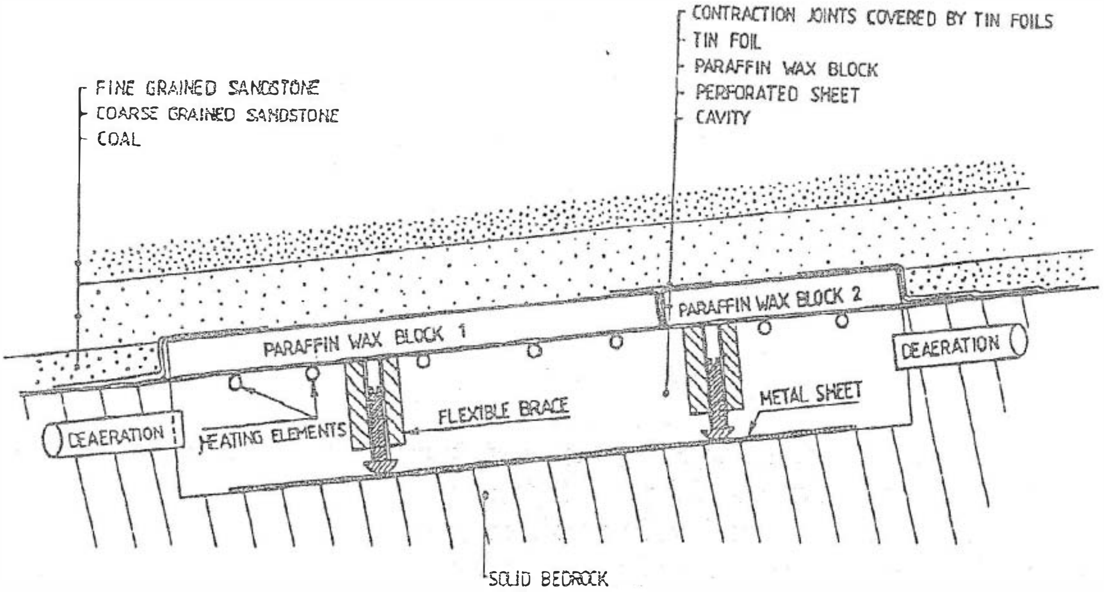

FIG. 3. Scheme of the exploitation space in the model

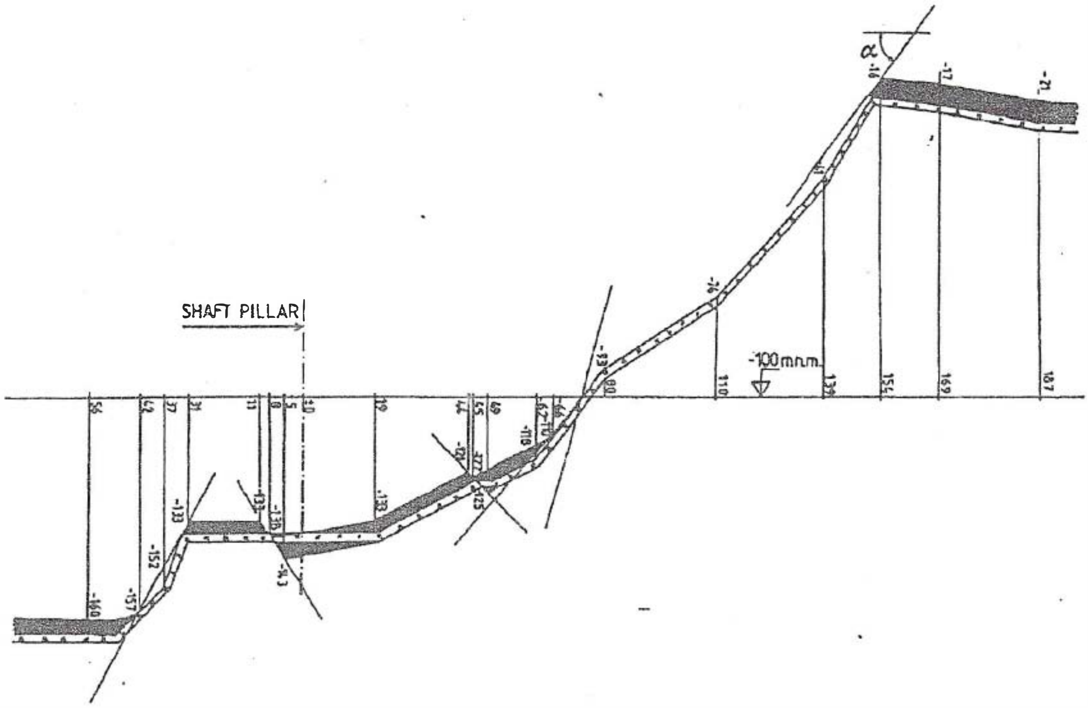

FIG. 4. Section normal to the direction of the main tectonic fault in the model space

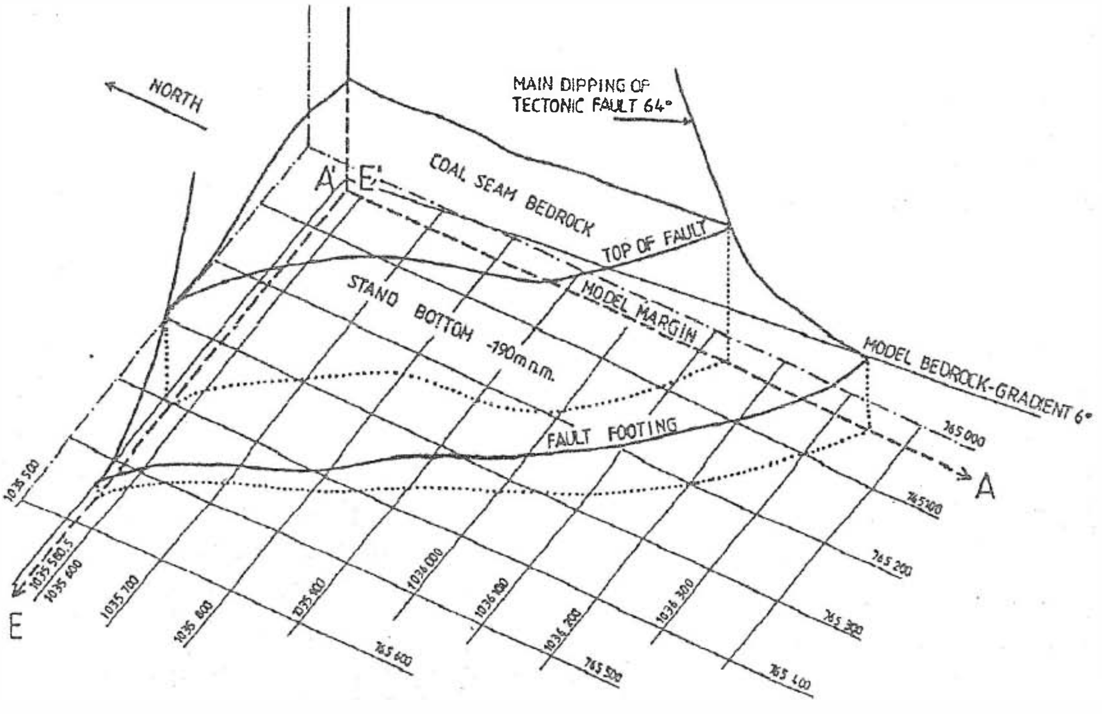

FIG. 5. Course of the main tectonic fault in the model

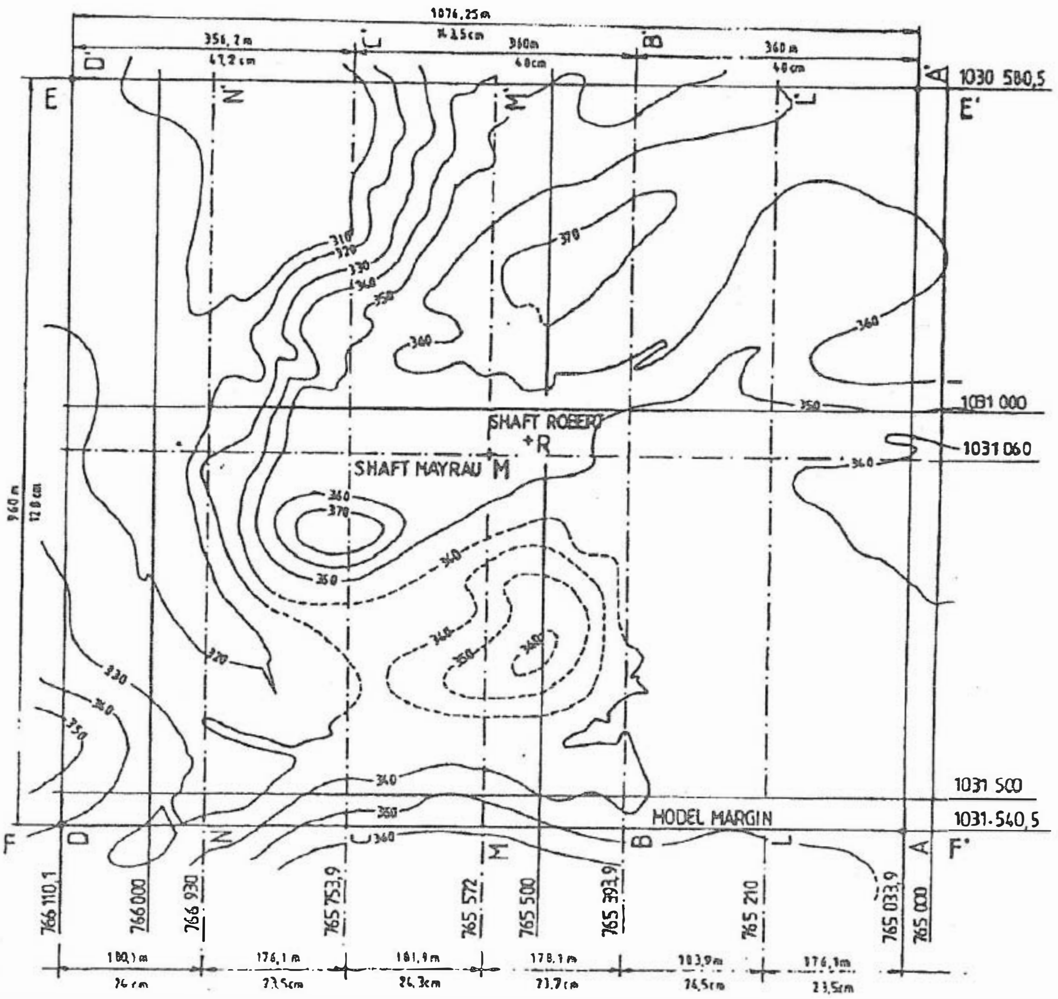

FIG. 6. Surface of the modelled area

COURSE OF THE MODEL EXPERIMENT

The extraction of the coal seam simulated, in the model by paraffin plates, was realized by successive melting of paraffin parts. The entire time period was disposed into three phases of the experiment on model. Within the first phase, parts equivalent to blocks excavated during the years 1993–1996 were molten off; the second phase concerned 1997–1998, and the last one 1999–2000.

Basic couples of photographs of the model surface were taken prior to the first phase. Fist, the part ① and subsequently the part ② (Fig. 8) were molten off. After a 24 hours' interval, the deformed model surface was intercepted by another couple of survey photographs. The interval between individual phases was determined empirically on the basis of testing models so that, at the time of exposition, the deformation process on the model surface would already be terminated. In the same way as the first phase, the second phase of the model experiment was carried out, during which parts ③, ④ and ⑤ were molten off and a new stereo-couple of

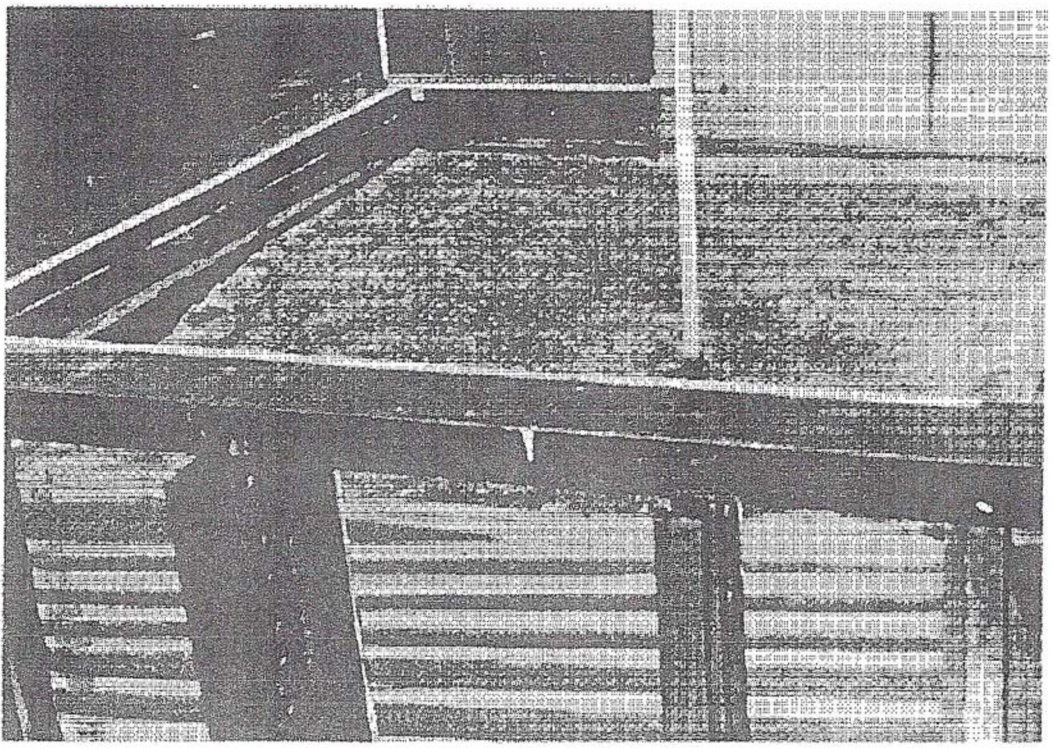

FIG. 7. Model prepared for the experiment

photographs was taken. The experiment was ended by taking survey photographs of the model surface after dieing away of deformation effects due to melting-off the parts ⑥ and ⑦.

It turned out, after exposing the molten paraffin blocks during the liquidation of model, that there remained, in marginal parts of individual blocks, unmolten remainder of paraffin (Fig. 9). This remainder represented totally about 20 % of the original paraffin quantity, the part ② being entirely molten off, while in the part ⑦, there remained about 37 % of unmolten paraffin. This was the first application case of the simulation method for modelling the progress of mining on a 3-D model. In spite of the fact that the equipment was tested before the experiment, these negative effects were caused by different heat conduction conditions within the enclosed model space. Owing to the fact that the recovery of the coal seam connected with mostly used mining methods in Kladno basin (room and pillar exploitation and slicing) is indicated to attain about 70 %, the results from the model are surely on the safe side.

EVALUATION OF THE MODEL EXPERIMENT. ANALYSIS OF PRECISION

Measurements of stereo-couples of photographs and analytical processing of the taken coordinates of detailed points on the model surface by the transformation stereophotogrammetric method resulted in the preparation of digital models of the surface, formed by rectangular spatial coordinates x, y, z. The surface deformation

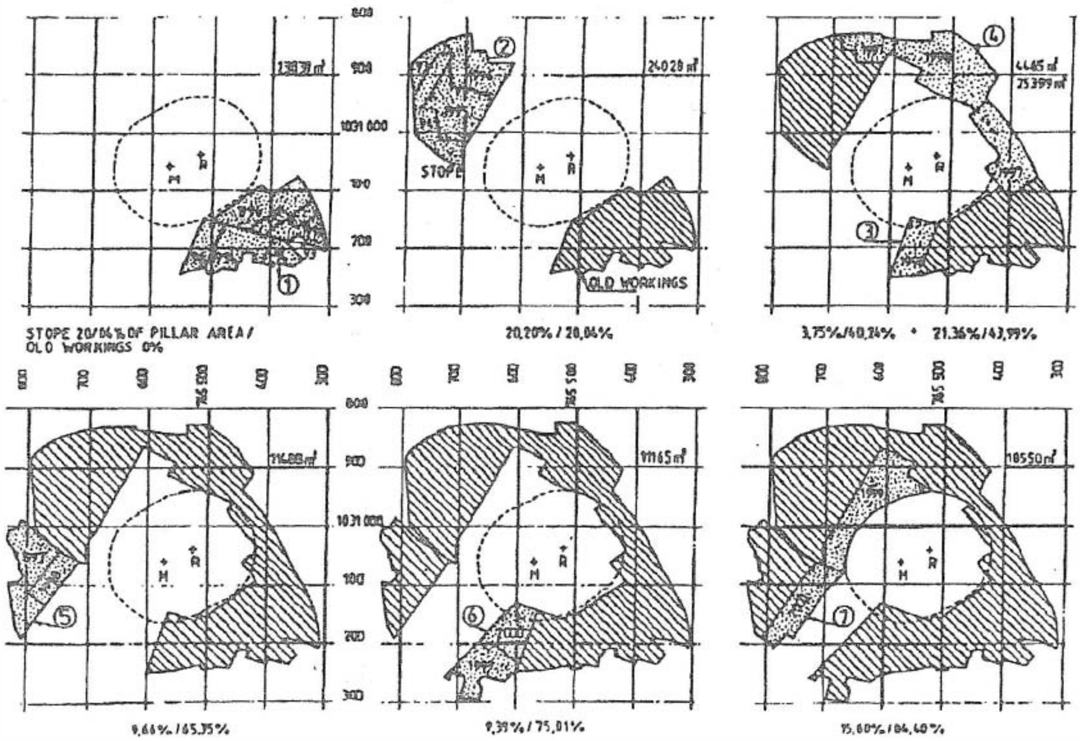

FIG. 8. Exploitation progress of the shaft pillar

was determined from coordinate differences, obtained for individual deformation conditions due to the extent of simulated coal seam extraction and coordinates of identical points on the model surface, determined before beginning of the experiment. Deformation components *dx*, *dy*, *dz* were processed graphically in the form of isolines.

Fig. 10 illustrates vertical deformations of the model surface for the condition, which would take place after drawing a part of the coal seam according to the planned mining progress during 1993–1996 and after complete dieing away of the deformation process on the surface. A subsidence basin with two marked depressions above sites, where the excavation was simulated, was formed on the model. Maximum recorded vertical deformation attained 1 mm on the model, which corresponds to 75 cm in real conditions.

If the extraction of the shaft pillar would be brought to the end in the year 1998 and all parts planned for this period would be mined off, the vertical displacement in real conditions, after dieing–away of the deformation process on the surface, should attain 150 cm according to the results of model experiment (Fig. 11).

For conditions in the year 2000, when all blocks ① to ⑦ (Fig. 12) would be extracted, a maximum vertical deformation of about 200 cm can be assumed. The extent of the subsidence basin is clearly evident from figures.

Values of vertical displacements established on the model do not include displacements, which took place in consequence of previous exploitation in the neighbourhood of the shaft pillar prior to the year 1993 and which were eventually recorded

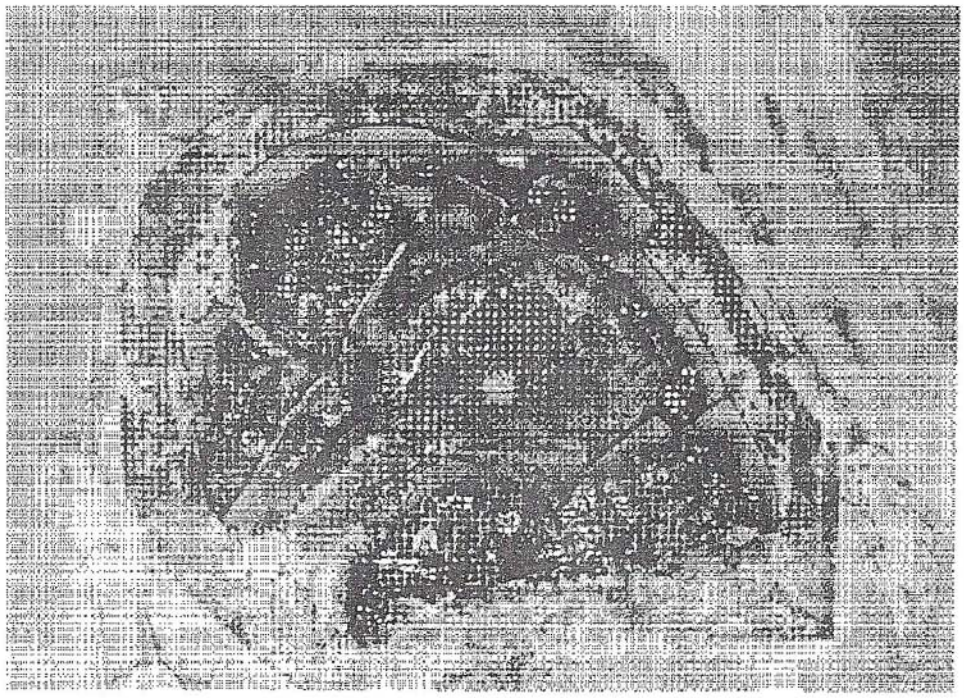

Fig. 9. Unmolten residuals of paraffin after the end of model experiment

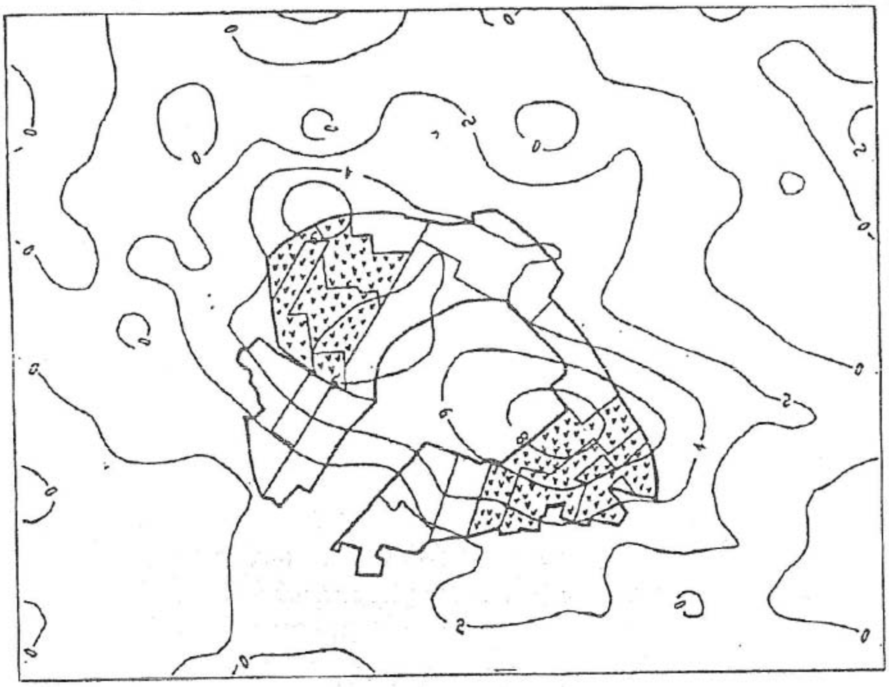

Fig. 10. Vertical deformations of the model surface (in 0,1 mm) due to exploitation till 1996

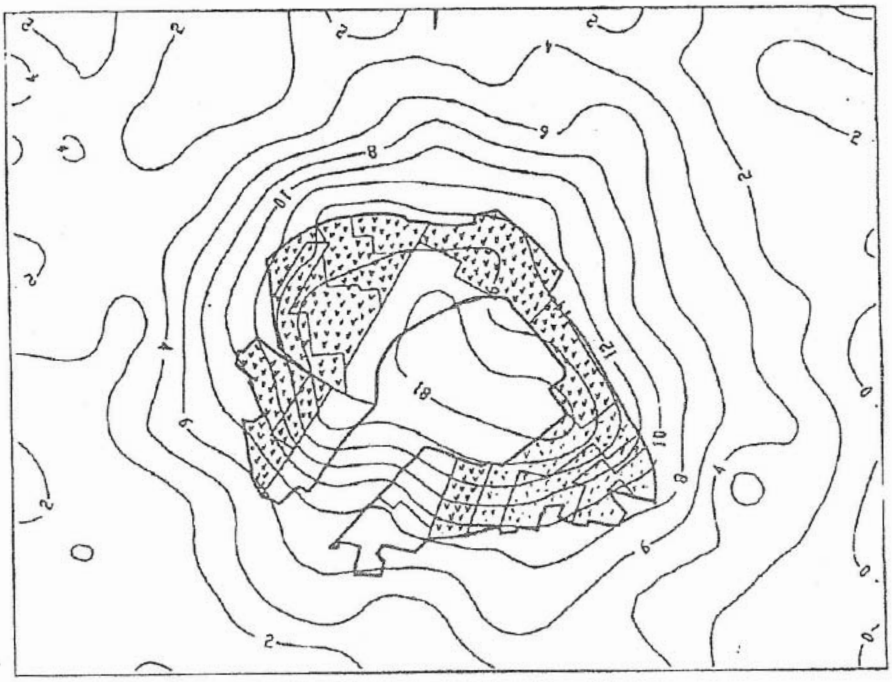

FIG. 11. Vertical deformations of the model surface (in 0,1 mm) due to exploitation till 1998

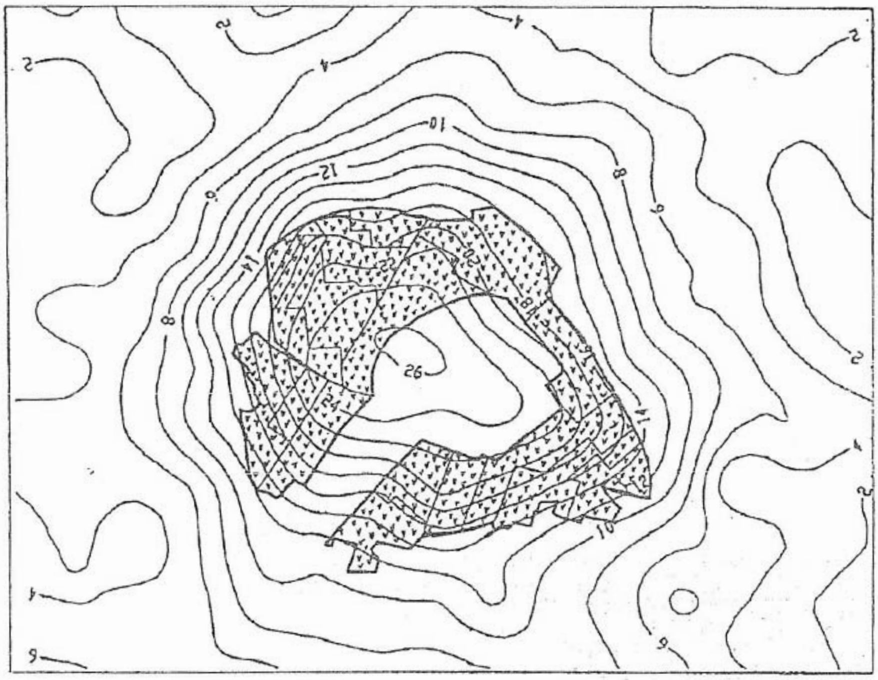

FIG. 12. Vertical deformations of the model surface (in 0,1 mm) due to exploitation till 2000

here by previous levelling measurements.

As already mentioned, the precision of the stereophotogrammetric method of determination of horizontal deformations in the direction parallel to the shot axis is much lower than in the direction perpendicular to this axis. As there is no reason, why a principal difference should exist in displacement values in both of these directions, it is possible, for determination of maximum horizontal displacements, to use values established in the direction perpendicular to the shot axis. In consequence of mining activities realized till 1996, maximum horizontal displacements up to 30 cm above the external border of the shaft pillar towards the centre of the subsidence basin may be assumed, till 1998 up to 45 cm, till 2000 about 60 cm. Horizontal displacements of up to 15 cm have been measured within the area of the shafts Mayrau and Robert.

The overall precision of the assessment of surface deformations due to undermining by the physical modelling method depends, above all, on the precision of input data required for the construction of the model, which include:

- information on geological situation,
- geometry of the modelled area,
- physical and mechanical properties of rocks.

In addition to inaccuracies of these basic data, which affect also in the numerical methods [Havlík, 1967], errors of the proper modelling method must be taken in account, too. These depend particularly on the model scale and on the connected generalization of input data, then also on the technical possibilities to determine the corresponding properties of equivalent materials, which substitute, in the model, the rock material medium. The overall precision is also affected by the already mentioned average error of the applied measurement and evaluation method of deformations of the model surface.

It is evident, that the overall average error of surface deformations, which is given according to the law of error cumulation, by relation

$$m_S = \pm\sqrt{m_1^2 + m_2^2 + \ldots + m_i^2}\,,$$

where $m_1, \ldots, m_i$ are average errors of individual factors, taking part in the model experiment, cannot be determined exactly. It is advisable, for the evaluation of reliability of results obtained from the model, to repeat the model experiment. Results of the model solution can be confronted, qualitatively and quantitatively with simple numerical methods used for preliminary calculations of surface subsidence or, more reliably, to carry out a model solution for an area, where the effects of undermining on its surface are already known.

It may be started, in conclusion, that the suggested method of successive demelting of paraffin blocks which, was used for simulating of underground mining on 3-D physical models proved successful. In spite of the small scale, which had to be chosen due to the extent of the modelled territory, the method complied with the expectations. It has been proved that physical models could be adequately used for the solution of problems of narrower extent, namely in areas with complicated geological structure (e.g. fault zones), provided models could be constructed in larger scales.

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