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REPEATED LEVELLING IN THE MAYRAU MINE AREA USING UNDERMINING INFLUENCE THEORIES

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ABSTRACT
During the 1970's the extraction of coal approached the shaft-pillar of the Mayrau Mine, and it became necessary to check the effects of the mining on the mine objects. Consequently, a local levelling net, which was extended into the area of the Vinařice Penitentiary at the beginning of the 1990's, was set up in the area of the mine at the beginning of the 1970's. The periodic levelling of the original net had been repeated since 1975 at approximately five-year intervals. Since 1992, when the extraction of coal began in the shaft-pillar of the Mayrau Mine, the original and extended net was levelled at yearly intervals. This levelling served to check the increased hazard of damage to surface objects of the mine and the Penitentiary. The minefield of the Mayrau Mine is now no longer being exploited, because mining was irreversibly terminated in 1997. However, the repeated levelling of the net as a whole continued until 2002, its purpose being to document the surface after-effects of undermining. All the results of this levelling have been reported in this paper. Their analysis was carried out with a view to the shape of the subsidence basin created as a result of the mining operations, and conclusions were drawn with regard to possible hazard to surface objects. The gist of the conclusions drawn is in the comparison of the conducted levelling with the theoretical principles of undermining effects and in finding the most suitable theoretical model as a convenient tool for future study of subsidence in the Kladno District.
The work, described in this paper, was carried out as part of the Project "Targeted Research of the Academy of Sciences of the Czech Republic" number S 3086005.

KEYWORDS: levelling, shaft-pillar, theoretical model

INTRODUCTORY INFORMATION

At the beginning of the 1970's the exploitation in the working field of the Mayrau Mine (Kladno Mining District) approached the boundaries of and at the beginning of the 1990's it entered the shaft-pillar. In consequence of legal obligations to protect surface objects from the effects of undermining, the mine management organised the first measurements of the local levelling net, established well in advance to cover the surface objects of the mine, in 1975. The net was levelled periodically, originally at five-year intervals, and from 1992 to 2002 at yearly intervals. In 1993, the coal mining entered the shaft-pillar itself and, therefore, it became necessary to monitor carefully the effects of the exploitation on the mine's operational buildings, because the exploitation, planned in the shaft-pillar until the year 2000, was expected to have a significant effect on these surface objects (Vencovský, 1998a). This involved not only these objects, but also the objects in the immediate neighbourhood, in particular the buildings of the Vinařice Penitentiary. This was the reason why the original levelling network was extended into the Penitentiary precinct at the end of the 1980's and beginning of the 1990's. Figure 1 shows the location of the levelling points on the objects of the Mayrau Mine and of the said Penitentiary.

Intention of paper, the authors was to collected and publish all the above-mentioned levelling data, to establish the relations between the exploitation carried out and the measured subsidence, study the possible hazard to surface objects due to undermining and, in particular, to make use of these measuring data analytical to construct the most suitable theoretical model of undermining effects relevant to the mining and geological conditions of the Kladno District. This objective of the paper may, at this time, seem to be an end in itself, because all exploitation has been permanently terminated in the Kladno Mining District, and no new knowledge gained here has any practical application. Nevertheless, they could contribute to the theoretical factual basis of undermining effects on the Earth's surface, serve further studies of undermining effects in this mining district, and provide guidance in studying these phenomena in other mining areas.

The expansion of the levelling net into the area of the Vinařice Penitentiary and its periodical sighting nearly twenty years after the levelling of the original net led to creating three groups of elevation data, each relating to a particular area and time interval, in seeking the relations between the executed exploitation and the observed subsidence.

The group, hereinafter designated **7592,** concentrates the results of periodic levelling of a total of 37 levelling points, whose elevation changes include the effect of mining between 1975 and 1992, i.e. in a situation when the exploitation approached the boundaries of the shaft-pillar. The said levelling points belong to the original local levelling net and were stabilised exclusively with respect to the Mayrau Mine objects (Fig. 1).

The group referred to as **9302** contains elevations and their variations of a total of 74 points, which reflect the changes in elevation of the surface between 1993 and 2002, i.e. changes then associated only with the exploitation of the shaft-pillar in the years 1993-1997. This group of data covers a larger area relative to the preceding group, because it includes the results of periodic levelling of the original net, as well as its expansion into the area of the Vinařice Penitentiary.

The third group, designated **7502**, covers the same area as group **7592** and contains the results of periodic levelling of the above-mentioned 37 points over the whole period of this levelling, i.e. from 1975 to 2002. The changes in the elevations of the points of this group already reflect the penultimate effects of undermining resulting from all extraction work, carried out in the mine field of the Mayrau shaft from 1975 to the middle of 1997. Local experience indeed indicates that the subsidence of the surface will come to an end roughly in five to seven years after extraction has been terminated (Lucák, 1968).

The data of all these three groups are, moreover, supplemented by elevations from periodic levelling of several levelling points, which are stabilised within the broader vicinity of the mining field of the Mayrau shaft, and which belong to the extensive levelling net established in the area of the whole Kladno Coal Mining District by the Institute of Geodesy, in Prague (**IG**) during the past century. This levelling net acquired its present form and density in 1975, and since then the Institute levelled it periodically at yearly intervals until 1980. The interval of levelling was then extended and the levelling of the net was then carried out only in 1985, 1990, 1996 and 2003 (Vencovský, 2002). This involves a total of 12 points, which were selected from levelling traverses Bh20, Bh22 and Bh23, and which the author marked with indices 2008 through 2306. The inclusion of these points in all analyses carried out thereafter contributed effectively to the above-mentioned testing of and search for the most suitable theoretical model of the effects of undermining for the Kladno mining locality.

Some of the selected 12 points are indeed located at the bottom of subsidence basins (Fig. 2) and, therefore, are quite distant from the relatively small areas of all groups of elevation data **7592, 7502** and **9302**, which increases their testing, significance substantially.

The elevation data appropriate to the levelling points, which contribute to the configuration of all three groups mentioned, are listed in **Appendix 1** www.irsm.cas.cz/Newweb/staff/Vencovsky/priloha1.xls In Fig. 1 the rectangles indicate the areas of each of the above-mentioned groups of data without including the 12 levelling points of the **IG**. In view of the small number of these points and their distance from the point field of the original and extended levelling net of the Mayrau Mine, these points were significant for testing only. As regards the Introductory Information, it should be added that the repeated levelling of the original and extended net was carried out by the surveying group of the Mayrau Mine, and that it was in each case connected to the levelling point of the State Levelling Net designated Bh26.22, which is located in the object factory Kablo - Kladno. The elevation of this point has been checked since 1975 in the course of periodic levelling, carried out by the **IG**, and has to date displayed variations in the range of 1 cm only.

SURFACE SUBSIDENCE IN THE AREA OF THE MAYRAU MINE IN THE YEARS 1975-92

The surface subsidence in this locality is determined by the time variations of the elevations of a total of 37 levelling points, located exclusively in the Mayrau Mine area. The changes in elevations of these points were derived from the data given in **Appendix 1** by linear interpolation over the period 1975 to 1992, and form the data group **7592**, in which the subsidence of the 12 above-mentioned points, monitored during the periodic levelling of the **IG** (points 2008 to 2306) was included. The data in Column 4 of the said Appendix represent the subsidence (m) of the points and provably demonstrate the origination of the subsidence basin as the consequence of mining conducted since the beginning of the 1970's until the end of the second half of the 1980's. The situation overview and time schedule not only of these, but also of all mining operations are shown in Fig. 2, derived from a map (scale 1:1000) of these operations, provided for this purpose by courtesy of the Surveying Department of the General Directorate of the Kamenouhelné doly concern (Black Coal Mines) in Kladno. The flat coal at an elevation of –120 m to –180 m msl, approximately 7 to 8 metres thick, was blow board-and-walk worked and later extracted using the so-called V-system and modern mechanisation. The exploitation coefficient amounted to roughly 0.6. These data only concern the mining carried out during the 1970's. Later mining of so-called bottom coal in the 1980's was carried out only in old boards, where the thickness of the extracted seam was 2.5 to 3 m and the exploitation coefficient roughly the same. Figure 2 shows the objects of the Mayrau Mine, as well as the locations of the above-mentioned 12 **IG** levelling points.

The subsidence of the surface in the area of any of the data groups can best be described in terms of subsidence Isolines, which can be obtained from the digital model of the surface constructed from the dimensioned point field, formed by the position co-ordinates of the levelling points involved and the subsidence assigned to them. For this purpose it is most convenient to choose a model based on the application of the multi-quadric interpolation method, the principle of which the authors described several times in the specialised literature (Vencovský, 1984), (Vencovský, 1999).

The result of applying this method to the **7592** group of data (without the **IG** points) is shown on the l.h.s. of Fig. 3. The isolines depicted there indicate that the mine objects are located on the slope of the subsidence basin, which is inclined to the west towards the basin bottom.

An idea, albeit theoretical only, of the extent and shape of the whole subsidence basin can only be obtained with the aid of special software, which is able to predict subsidence with regard to actual data on planned extraction. One such software is Vencovský's, used at the beginning of the 1990's in connection with predicting surface subsidence due to the extraction being commenced in the Mayrau shaft-pillar (Vencovský, 1995a), (Vencovský, 1998b), (Vencovský, 1995b).

The results of applying this software in the form of subsidence isolines for the mining carried out in 1975-92 and the **7592** data area are shown in the other small pictures on the l.h.s. of Fig. 3 for various theoretical models of the effects of undermining to be discussed later. The isolines in the small pictures on the l.h.s. of Fig. 5 indicate the overall extent and formation of the subsidence basin, in each case corresponding to a particular theoretical model. In both cases the authors chose as the basic model of undermining effects the Bals model, or to be more precise, the model, which is based on the analytical form of the influence function, formulated by Bals in the first half of the past century (Neset, 1984). As we shall see from the facts mentioned below, it is indeed this, perhaps the oldest form of the influence function of all later formulations (Bayer, Perz, Sahn, Knothe, Kowalczyk), which yields the most satisfactory results of prediction and study calculations of subsidence with regard to the mining and geological conditions in the Kladno District. This fact has been and is generally known from the long years of experience of the Kladno mine surveyors (Lukeš, 1967) and is the reason why the author used it for this purpose in this paper. Nevertheless, the authors also endeavoured to support this fact. Using the above-mentioned software, the set of subsidence measurements **7592** from **Appendix 2** was used to seek the two principal parameters, which have a dominant influence on all results of subsidence prediction calculations. As these parameters one can consider, in the first instance, the already mentioned analytical form of the influence functions and also the value of the critical angle of influence (Neset, 1984), which is approximately 60^o to 65^o under the mining and geological conditions of the Kladno District (Lucák, 1968). Based on a series of experimental calculations, in which both the said parameters were varied, it was found that the already mentioned Bals influence function and critical angles of influence in the range of 56^o to 58^o satisfy the **7592** set of measurements best. The value of the angle is thus a little smaller than the range of values given above, which apparently corresponds to slightly changed mechanical and physical properties of the upper layers of the overlying rock massif due to the marginal effects of earlier mining. The results of these calculation experiments are given in **Appendix 2**. Columns 5 through 11 of this Appendix contain the differences between the observed and theoretical subsidence (m). The comparison of these differences clearly indicates that the theoretical subsidence if the value of the critical angle is 56^o to 58^o and the Bals influence function is used, comes closest to the actual subsidence. Other forms of the influence function, e.g., the Knothe influence function, or another function similar to it, are now mostly used in predicting effects of undermining. As indicated by the Appendix, the use of the Knothe function (Neset, 1984) is very problematic. Given an acceptable value of the critical angle, 56^o to 58^o, and using the Knothe function, the theoretical subsidence of some points displays substantially lower values than the actual, and, vice versa, too high values for points from the bottom of the subsidence basin (**IG** points 2014, 2015, 2305, 2306). For the theoretical subsidence according to Knothe to approach the real and, hence, the theoretical subsidence according to Bals, the values of the critical angle would have to be 44^o-46^o, which is contrary to practical experience. Nevertheless, the numerical agreement between the two theoretical models of subsidence effects, even using a speculative value of the critical angle, is very pronounced. The graphical results, shown on the l.h.s. of Fig. 3, support these findings.

The vertical sections are also definite proof of this in terms of the actual subsidence basin, as well as in terms of its theoretical models, shown in Fig. 4. This figure also evidently shows that the general inclination of the slope of the subsidence basin is approximately 0.2%, and that it varies within the range of 0.1% to 0.5%, which according to the criteria for mine damages (Neset, 1984) represents no substantial hazard for the buildings located here.

SURFACE SUBSIDENCE IN THE AREA OF THE MAYRAU MINE IN THE YEARS 1975-2002

Set **7502 (Appendix 3)** which covers the same area as group **7592**, was created from the Mayrau Mine levelling net for the purpose of determining the variation of surface elevations in this time interval. For the purpose of comparing the actual and theoretical subsidence, this set was also supplemented by the subsidence data of the **IG** points. The data were again processed in the form of a digital model of the subsidence surface for the above area. The result in terms of isolines is shown as the first small picture in the middle part of Fig. 3. This and also Fig 6 clearly indicate that the nature of the slope of the formed subsidence basin is very similar to the nature and shape of the slope of the basin, identified from the **7592** data. Only the slope subsided a total of approximately 30 to 40 cm, the general inclination of the slope and its changes remaining practically unaltered. Figure 6 and the values of the differences between the actual and theoretical subsidence of all points involved, listed in **Appendix 3** (Columns 5 through 11) clearly show that the model with the Bals influence function, provided the critical angle is considered in the range of 56 – 58^{o}, is again the most suitable theoretical model of the undermining effects. Also in this case good agreement is observed between this model and the model with the Knothe influence function, assuming the speculative value of the critical angle to be 46^{o}. This is supported by the isolines of subsidence basins for the separate theoretical models, shown in the other small pictures in the middle part of Fig. 3 and in Fig. 5, as well as by the differences between the actual and theoretical subsidence data, which are also given in **Appendix 3**. The model with the Knothe influence function, assuming the critical angle to be between 58^{o} and 60^{o}, is quite unsuitable. In this case the theoretical subsidence of the basin bottom would amount to nearly 2.6 m, which disagrees significantly with the results of the most recent **IG** levelling in 2003, when the actual subsidence of points (points 2015, 2015, 2305, 2306), located in the area of the basin bottom, amounted to approximately only 1.7 m **(Appendix 3, Fig. 5).**

As regards the possible hazard to surface objects due to the inclination of the subsidence basin, the same conclusion as in the preceding analysis can be drawn from the information provided by Fig. 6. The general value of the inclination remained the same, which also applies to the changes in the inclination along the basin section running along the axis of the **7592** area, which does not represent a more substantial risk as regards damage to these objects due to undermining.

SURFACE SUBSIDENCE IN THE AREA AND NEIGHBOURHOOD OF THE MAYRAU MINE IN THE YEARS 1993-2002

The nature and extent of these subsidence phenomena can be derived from the analysis of elevation variations of levelling points of the original and extended levelling net of the Mayrau Mine, grouped in data set **9302**. The results of this analysis can only be considered approximate, because the elevations of the points of this net for the beginning of 1993, when the extraction of the mine pillar began, can be determined only approximately. The reason for this are the lengthy time intervals in repeating the levelling of the original levelling net (1985, 1990, 1994). Indeed, the elevations of all points of the net at the so-called “Zero Stage” have to be derived, i.e. their elevations at the end of 1992, because the mine’s shaft-pillar began to be mined at the beginning of the subsequent year. In the extended part of the net, these elevations, with a few exceptions, were determined in the levelling of the basic stage in 1992. However, these elevations of the points of the original net have to be derived from the levelling stages of 1985, 1990 and 1994. As can be seen from **Appendix 1**, the elevations of all the points in this part of the net display a moderate, but systematically growing decrease. Between 1985 and 1990 this was apparently due to the after-effects of the subsidence phenomena caused by the extraction in the 1970’s and the residual mining in the first half of the 1980’s. The changes in elevation between 1990 and 1994 were probably already caused by the extraction of the mine’s shaft-pillar, begun in 1993. In the given situation there is but one solution: to determine the elevations of the points in this part of the net for the said Zero Stage by linear extrapolation from the changes of their elevations in the period 1985-90 for the end of 1992, and thus to take into account the after-effects of the mining in the 1970’s and 1980’s.

The decreases in the elevations of the points of the whole net, beginning with the Zero Stage in 1993 and ending with the last levelling in 2002, are given in **Appendix 4**, to which the decreases in the elevations of the selected **IG** levelling points have again been added. The digital model of the subsidence basin in the area extent of the **9302** data, expressed in terms of isolines, is depicted in the upper small picture on the r.h.s. of Fig. 3. The theoretical models of this basin in terms of isolines are also shown below this upper picture. As in preceding analyses, various models of undermining effects were again tested using the Bals and Knothe influence functions and the chosen interval of values of critical angles. The results of these tests are also shown in **Appendix 4**, and once again, although not as clearly, they lead to the same conclusion: The Bals subsidence model fits the real shape of the subsidence basin best. This is reflected much better in the small pictures on the r.h.s. of Fig. 5, which show the general shapes and extents of the theoretical models of the subsidence basin considered in terms of isolines. The graphs of the vertical sections in Fig. 7, taken along the axis of the area of the **9302** data, provide even better proof of this, as regards the actually created basin, as well as its theoretical models.

Figure 7 also clearly shows that the surface objects within the whole net (Fig. 1) have adopted positions, as a result of the subsidence in the years 1993-2002, on the slope of the subsidence basin with a general inclination of approximately 0.1%. Figure 7 further indicates that the inclination of this slope varies between 0.1 and 0.4%, which can again lead to the conclusion that the stability of these objects has in no way been seriously impaired by the undermining. Nevertheless, the change in the inclination in the neighbourhood of the location with co-ordinates y=-765400 is quite considerable, and the radius of curvature of the subsidence basin in this place is approximately 5 to 7 km.

In view of the standards used for mine damages, these values indicate that the surface objects may have already been subject to more substantial deformation effects at this location. A similar, but not as serious situation can be identified at the location with co-ordinates y = -765600.

SUMMARY OF CONCLUSIONS

The above analysis of periodic levelling in the area and neighbourhood of the Mayrau Mine enables the following conclusions to be drawn:

- The mining in the mine field of this mine, carried out from the beginning of the 1970's until the termination thereof in 1997, caused the subsidence of the surface only to such an extent that, in general, the building objects, located there, are not subject to any more serious danger. These objects are now located on the slope of a subsidence basin, the general inclination of which is approximately 0.2 % (2 mm/m) and varies along the section, drawn through the basin roughly along the axis of the surface built-up area, from 0.1 to –0.4%. Nevertheless, a detailed analysis of the shape of the section through the said slope points to the vicinity of the western boundary of the Vinařice Penitentiary where, due to the created curvature of the subsidence basin, deformation effects visible on buildings may have already occurred.
- To-day, i.e. approximately 7 years after irreversible termination of all mining, all effects due to undermining on surface objects can be considered as ended, although negligible after-effects may still appear in the results of future levelling.
- The analytical comparison of the results of periodic levelling with the theoretical principles of undermining effects leads to the conclusion that, in studying and predicting the subsidence of the surface in the Kladno Coal Mining District, the Vencovský's software, enabling computer realisation of the theoretical model of undermining effects for a given mining situation, for various modification of the analytical form of the influence function, and for various values of the critical angle of influence, can be used to an advantage.
- Based on calculation experiments using the above-mentioned software, it is recommended, with regard to the mining and geological conditions of the Kladno Coal Mining District, to use the Bals influence function and values of the critical angle of influence of 56-58^{o} as the most suitable. The range of the angle is slightly lower than the range of 60-65^{o}, which has in general been applied in the Kladno area. This most recent finding is apparently associated with the general change of mechanical and physical properties of the overlying massif due to more than one hundred years of extraction of Kladno coal. The results of the above experiments are summarised in Tab. 1, which has been compiled from the most important data in **Appendices 2, 3** and **4.** These Appendices, due to the extent of numerical data

Table 1 Summary of test result of theoretical models of undermining

Group		B56	K56	B58	K58	B60	K60	K46
	RA	**0.122**	0.226	**0.127**	0.272	**0.143**	0.321	**0.089**
7592	**Rmin**	**-0.300**	-0.483	**-0.332**	-0.594	**-0.380**	-0.702	**-0.171**
	Rmax	**0.329**	0.351	**0.308**	0.404	**0.332**	0.464	**0.256**
	RA	**0.113**	0.225	**0.125**	0.271	**0.150**	0.324	**0.101**
7502	**Rmin**	**-0.301**	-0.664	**-0.337**	-0.758	**-0.330**	-0.848	**0.175**
	Rmax	**0.362**	0.421	**0.395**	0.460	**0.408**	0.543	**0.296**
	RA	**0.050**	0.064	**0.044**	0.070	**0.054**	0.078	**0.065**
9302	**Rmin**	**-0.111**	-0.243	**-0.116**	-0.276	**-0.127**	-0.328	**-0.088**
	Rmax	**0.117**	0.086	**0.101**	0.113	**0.085**	0.102	**0.157**

RA	Average absolute value of difference	B	Bals influence function
R min	Minimum value of difference	K	Knothe influence function
R max	Maximum value of difference	46,56,58,60	Influence angles

they contain, have been appended to the article only in electronic form as files of the *.xls type, available at the web address www.irsm.cas.cz/Newweb/staff/Vencovsky/priloha1.xls (priloha 1 - 4).

- Collecting and publishing the results of periodic levelling, carried out over more than 25 years, may become valuable material for studying other terrain elevation changes in this locality.

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APPENDICES

Appendix 1: Results of measuring the changes in the elevations of levelling points in the Mayrau Mine area.

Appendix 2: Data set 7592

Appendix 3: Data set 7502

Appendix 4: Data set 9302

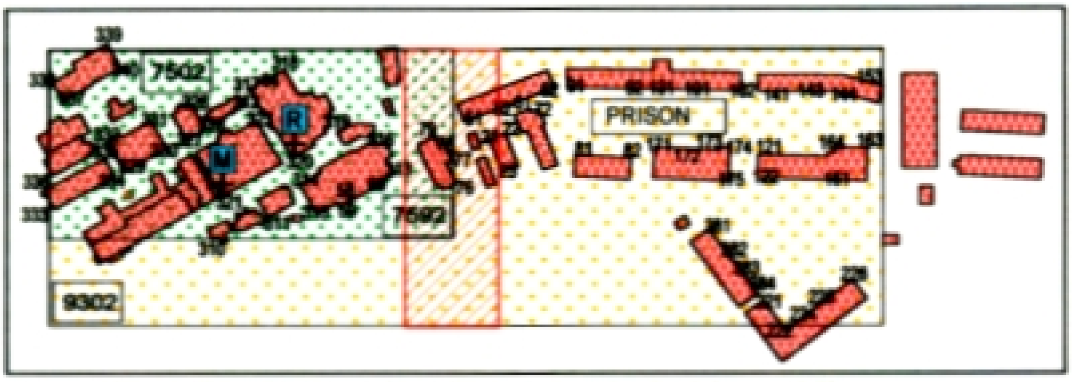

Fig.1 Distribution of levelling points in the Mayrau Mine area

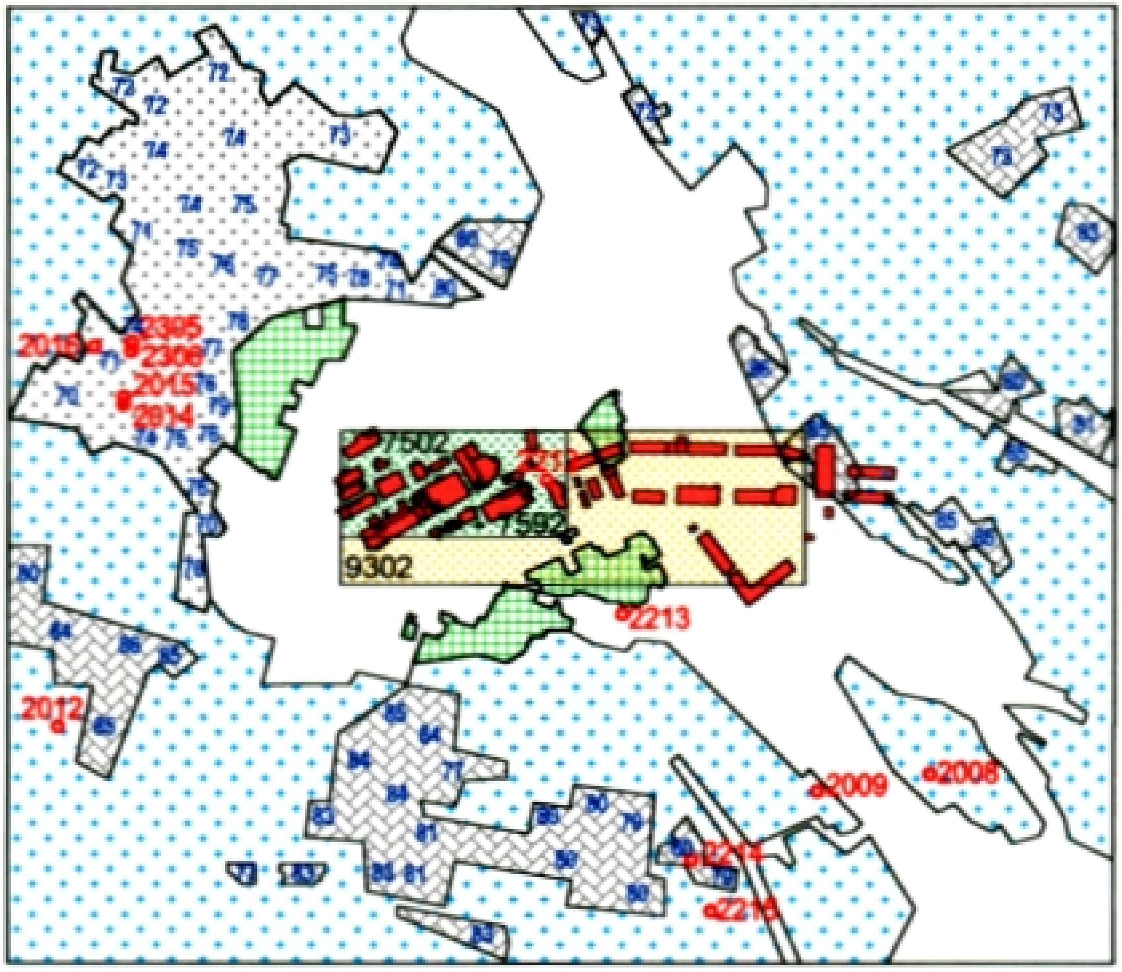

Fig.2 Mining operations in the mining field of the Mayrau Mine

mining operation 1972-80, seam thickness approx. 7 m, exploitation coeficient 0.6

mining operation 1977-85, seam thickness approx. 2,5-3 m, exploitation coeficient 0.6

mining operation 1993-97, seam thickness approx. 7 m, exploitation coeficient 0.6

mining operations from the begining of the 20th century to the end of the 1960´s

2008 - 2306 levelling points of the Institute of Geodesy

70 - 86 years of mining operations

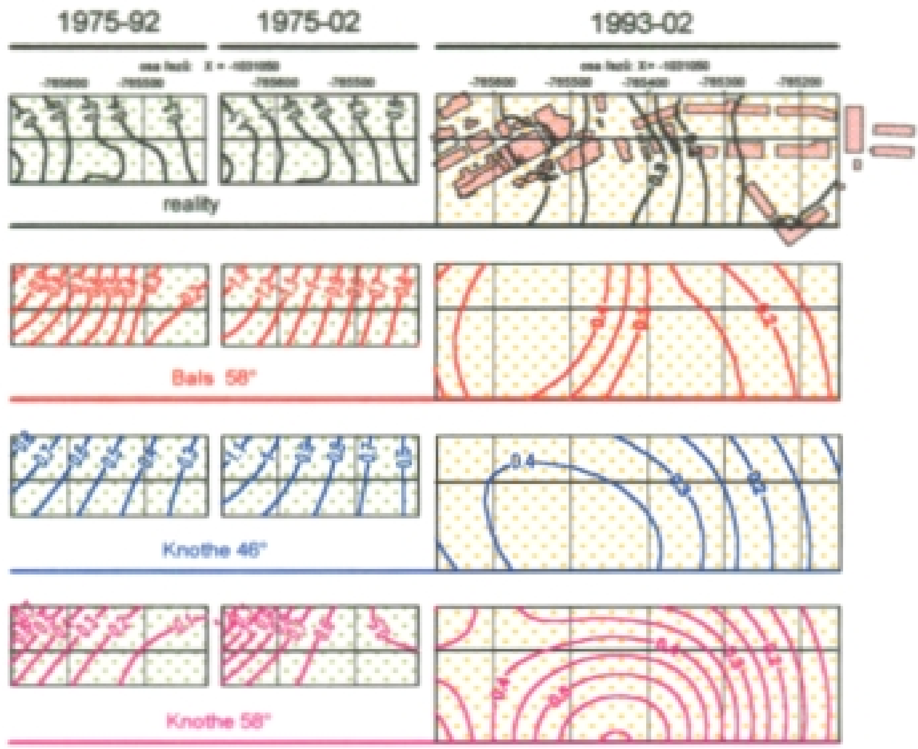

Fig. 3 Isolines of subsidence and theoretical models of subsidence in areas 7592, 7502, 9302

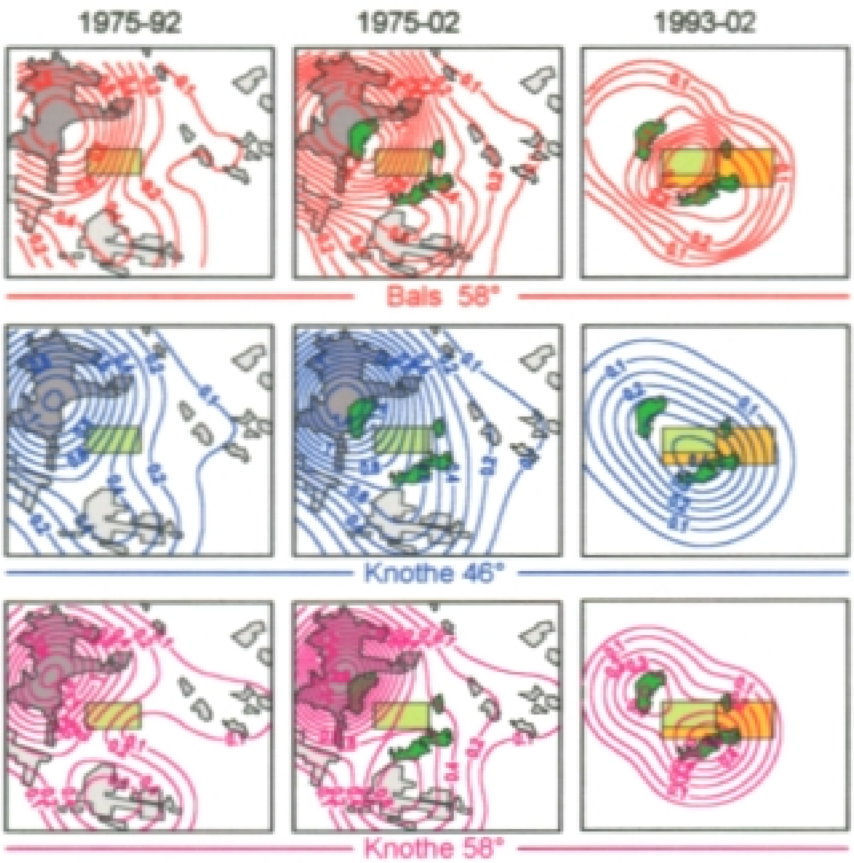

Fig. 5 Teoretical models of the overal shape of the subsidence basin for mining in years 1975-1992, 1975-2002, 1993-2002

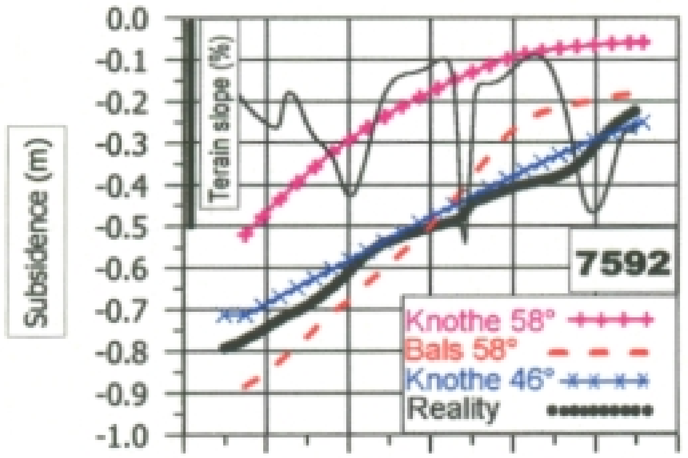

Fig. 4 Vertical section through the subsidence basin and its theoretical models in area 7592

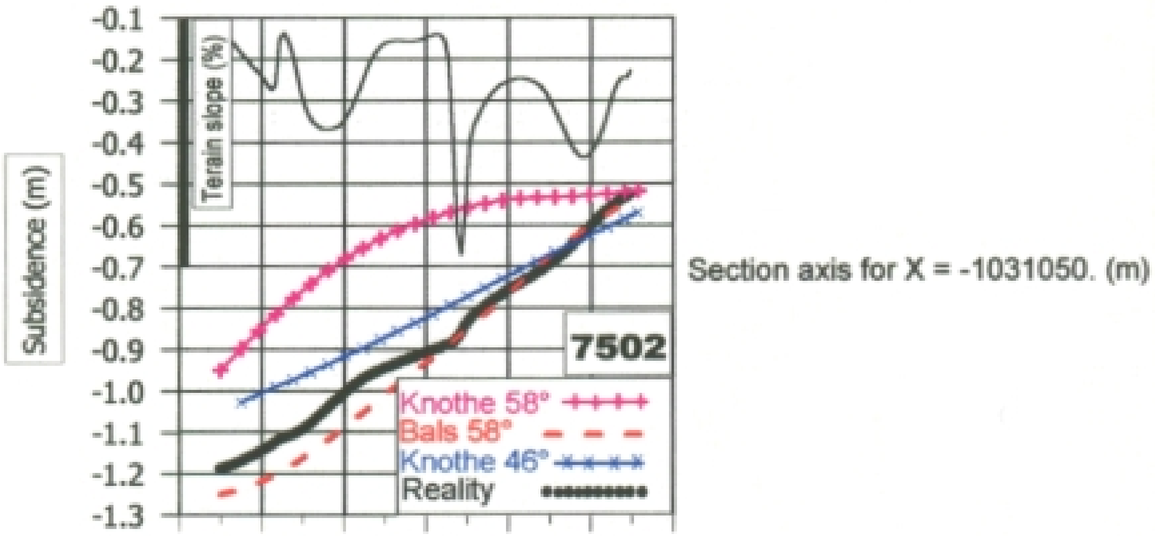

Fig. 6 Vertical section through the subsidence basin and its theoretical models in area 7502

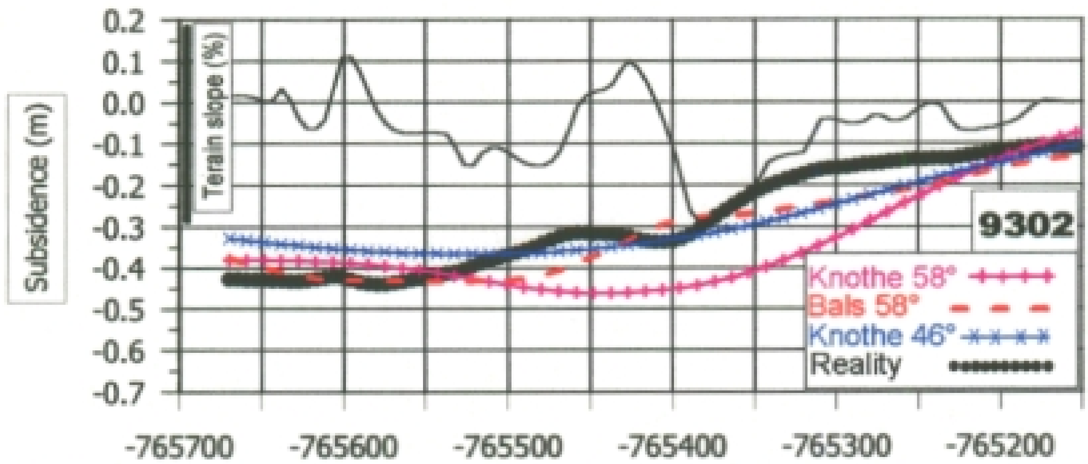

Fig. 7 Vertical section through the subsidence basin and its theoretical models in area 9302