Prace Instytutu Mechaniki Górotworu PAN
Tom 20, nr 1, Marzec 2018, s. 33-44

Scientific Importance of the Academic Achievements of Professor Knothe for Ground Movement Calculation in Germany

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Abstract

In Germany subsidence on the surface as a result of underground coal mining are known since 1850. In 1860, first height measurements are carried out. With this data mining subsidence, engineering starts in Germany (1st period). The results of this first period only refer to subsidence.

The "Trough Theory" of Lehmann (1919) essentially characterizes the 2nd period of research. The basic model of the ground movement elements and their interrelationships are defined. On this basis, different calculation procedures are developed.

In the time after World War II (3rd period) different distribution functions of subsidence based on mathematical models are developed as well as empirical profile curves.

In Poland, Professor Knothe introduces the calculation method based on the theory of stochastic media in 1953. It was 1959 before the ideas of Professor Knothe are published in German language. Very quickly, Professor Knothe´s model is picked up and in 1969, Erhardt and Sauer develop a computer software (Ruhrkohle Procedure).

The author follows up with the theory of Professor Knothe during his thesis on horizontal ground movements. It is evident that horizontal movements of the measuring points change their direction continuously. At any time, all measuring points have the same destination point of their horizontal movements, which is called the focal point of impact. A qualitative correlation of the position of the focal point of impact and the panel speed is proved. It is confirmed by measurements that the change of the panel speed brings additional dynamics in the process of horizontal movements

In the years 1999-2002, when Poland is still not an EC Member, the Institute IMG PAN attends a EU research project as guest. The aim of the Polish part project is to clarify the impact of the occasional cessation of face advance on the course of ground movement and deformation. The essential points are quoted from the final report of the EU project.

Professor Knothe made a significant contribution to scientific work in Europe by the establishment of the Institute of IMG PAN and his activities in international research.

Keywords: Subsidence Engineering, Horizontal Movements, Longwall Speed

1. Introduction

In many respects, the name of Professor Knothe is closely linked to subsidence engineering in Germany. Some examples will show how Professor Knothe´s theory, his expertise, publications, and the academic work of his IMG PAN Institute have positive influence in Germany and Europe.

First, a summary will be given about the development of mining subsidence engineering in Germany since the 19th century. Then, the author reports on a research about horizontal movements and the influence of longwall velocity, which stand in close accordance with the research of Professor Knothe. Topic of the last section is an EC Research Project in the years 1999-2002, where Professor Knothe was very actively engaged.

2. History of Mining Subsidence Engineering in Germany

In Germany large area subsidence on the surface because of underground coal mining are known since the middle of 19th century. Mining is active in deep depth, a correlation between working area and subsidence area is known, but the distribution of the subsidence is not predictable.

Most impacts of subsidence can be seen at railway lines so that the railway companies start height measurements in 1860 (Weissner, 1956 et al.). Using this data, mining subsidence engineering starts in Germany (1st period). Scientific contributions are published here and in other countries like France, Poland, England (Dumont, 1871; Jicinsky, 1876; Hausse, 1885; Korten, 1909 et al.). Goldreich (1913) summarizes the results of this first period of subsidence engineering, but only refers only to the vertical component of the movements.

The "Trough Theory" of Lehmann (1919) essentially characterizes the 2nd period of research. The basic model of the ground movement elements subsidence, tilt, curvature, displacement, strain and compression and their interrelationships are defined. The first practical procedure to calculate subsidence is developed by Köhne (Mine Surveyor of a Dewatering Association) using a simple formula and a spider grid. On this basis, more calculation procedures are developed (Keinhorst, 1928; Bals, 1931/32).

In the time after World War II (3rd period) different distribution functions of subsidence based on mathematical models should be mentioned: Perz (1948) with empirical profile curves as well as the rock mechanical theories of Beyer (1944).

In the 1960s, the method of finite elements (Zienkiewicz u. Cheung, 1967; Kratzsch, 1975) is used for calculating with the help of electronic data processing.

In Poland in 1953, Professor Knothe introduces a calculation model based on the theory of stochastic media (Litwiniszyn, 1953; Knothe, 1953). The division of Europe characterizes the 1950s, so that Knothe´s model theory is not made public in German language. It was not before 1960 that Bräuner (Bräuner, 1960) publishes the ideas of Professor Knothe in German language. After that, Knothe´s model is picked up all over West Germany.

In 1969, Erhardt and Sauer develop a computer software (Ruhrkohle Procedure) which is based on the stochastic theory and the model of Professor Knothe. In the 1980s, the Ruhrkohle Procedure makes way for the program "CAD Berg" developed by Wieland (1984) which is still in use today.

3. Horizontal Movements and Professor Knothe

The author follows up with the theory of Professor Knothe during his thesis on horizontal ground movements in the years 1999-2002:

– Measurements of Horizontal and Vertical Movements

Direct measurements of vertical and horizontal movement can be done by levelling and traverses, since about 1980 with aerial measurements. These measurements are carried out in spite of high costs only in a period of minimum one year.

Since the 1990s, such measurements are realized by GPS technology at intervals of one month. The special measuring method of Differential-GPS (DGPS) is used with a basis receiver on a surface point out of the influence area and many rover-receiver points inside that area. In several cases RAG AG supports mining projects with GPS measurements from the beginning of working until 6 months, after depleting in a four-weeks measuring rhythm (DMT 1999, 2000). Some practical results were reported several times (Sroka, 1999; Ballhaus et al., 2000). However, only individual aspects such as object controls or movement behaviour of single surface points are described. However, the available data material allows describing and analysing the movement of all measurement points within the sphere of influence extensively.

– Analysis of Measurements

The horizontal, vertical, and therefore the spatial line of movement of a surface point can be presented graphically very good due to the short measurement intervals. An example is panel 537 of a Mine in the western Ruhr Area (Fig. 1).

Point 25 of panel 537 is approximately 30 m of beside the middle of longwall face so that the horizontal movement should move to the left, assuming that the focal point of impact is situated in the middle of the panel. The horizontal track approaches the longwall up to epoch 13. Then at epoch 14 and 15 – shortly after

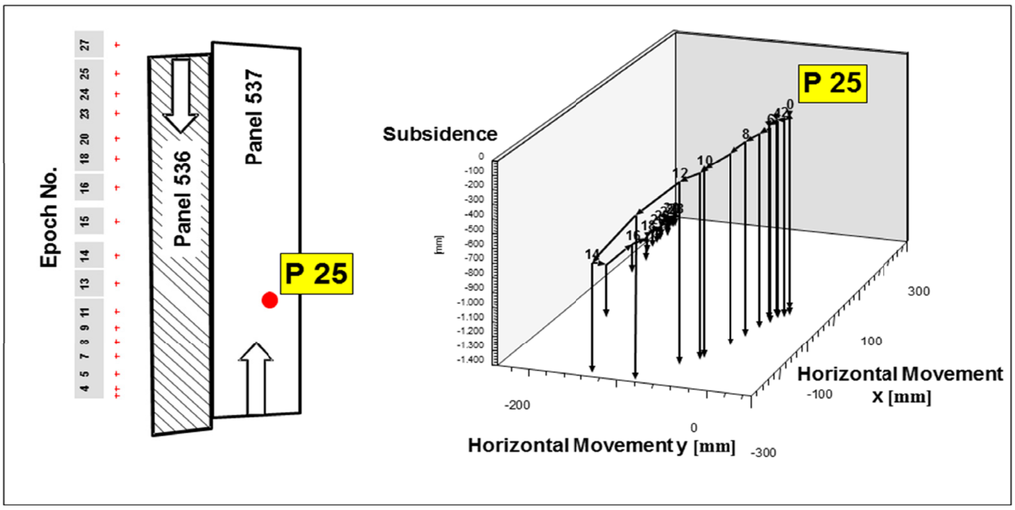


Fig. 1. Exemplary movements: Point 25 above Panel 537, Western Ruhr Area (Hegemann, 2002)

undermining – direction changes very strong with tendency to the left. Here, movement potentials affect from the former neighbouring panel 536.

This example demonstrate that the surface points change their horizontal direction very quickly and permanently depending on their position to the panel. The points follow a focal point of impact, which constantly changes its position.

In this connection, some definitions on the focal point of impact may be useful. The constant change of direction of the horizontal movement implies a continuous displacement of the focal point of impact. In literature it is defined and discussed differently. Strictly model-theoretically, the focal point of impact exists only for an elemental panel element in a homogeneous, isotropic rock mass. Several authors described focal point of impact from their practical experience (Fläschenträger, 1938; Perz, 1944; Niemczyk, 1949). Now a distinction can be made between the following definitions:

– Focus of an excavation area

Focus of an excavation area means that it is the geometric centre of a panel area and all surface points in the all-over impact radius moving towards it.

– Focus of a surface point

In other cases, the "focus of a surface point" is addressed. The focus implies influences from all different mining panels within the all-over impact radius (cone of impact) to this surface point. Each surface point has its own focus and moves towards it.

– Focal point of impact of a mining panel (Fig. 2)

Looking at the horizontal movements of all surface points within the area of influence of a panel over a certain period a common "vanishing point" of point movements can be recognized (Korittke, Sroka, 1998). This current focal point of impact of a panel in operation is characterized by the movements of all points in the changing influence area to this moving focal point. The influence area is that zone which generates ground movements even with time lag up to a zero line.

– Calculated focal points of impact

The evaluation of the measurements (panel 537) allows representing the horizontal movement vectors of 50 points for every epoch, for example movement directions between time 0 and 13 in Fig. 2.

It is to see clearly that all measuring points aim at one point, located roughly in the geometric centre of the mined area. This calculation can be done for each period for example epoch 1-2, epoch 2-3, epoch 3-4 etc. As result, we have some individual focal points of impacts for each epoch and we have with different positions for each period.

Fig. 3 shows the horizontal plan with the positions of all focal points of impact of panel 537 between epoch 4 and 27. For example, point 14 in figure 7 is the focal point between epoch 13 and 14.

Now all distances x_s of each focal point of impact to the longwall face distances are calculated for the epochs 4 to 26.

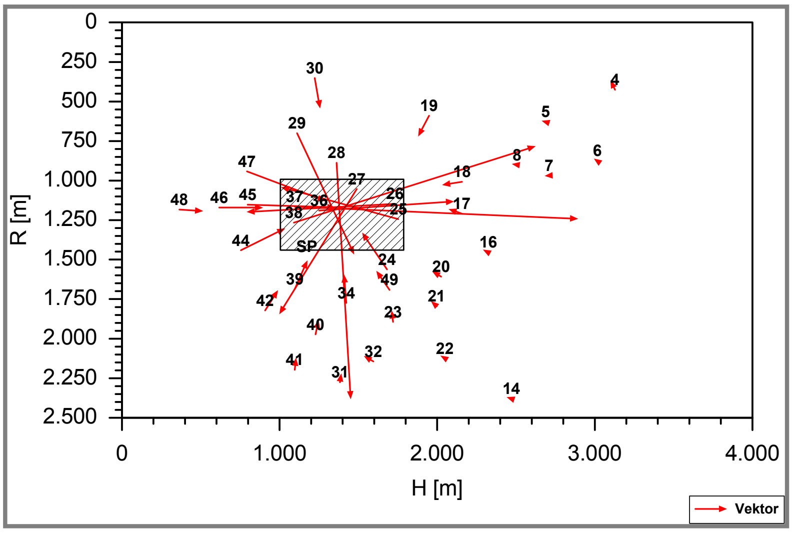


Fig. 2. Position of focal point of impact of a Panel (Hegemann, 2002)

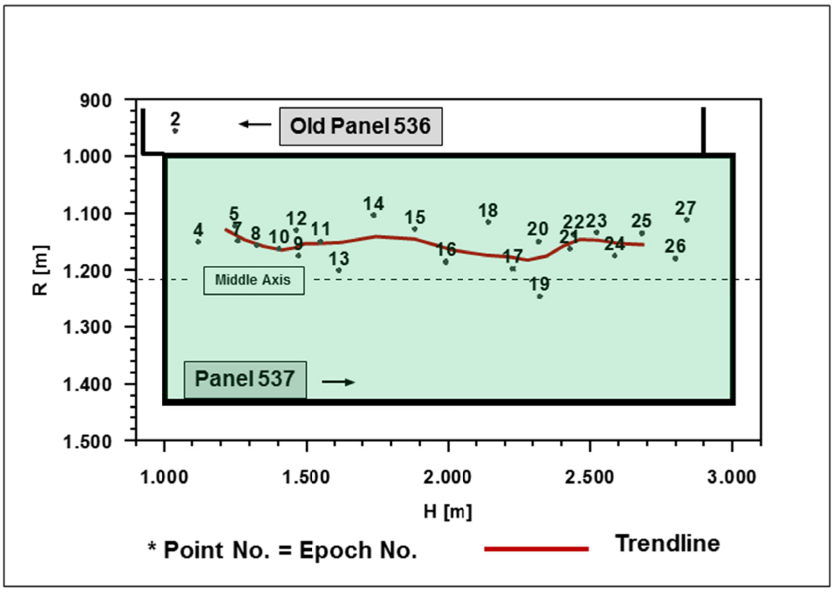


Fig. 3. Positions of focal points of impact in the panel area/ epoch 2 – 27 (Hegemann, 2002)

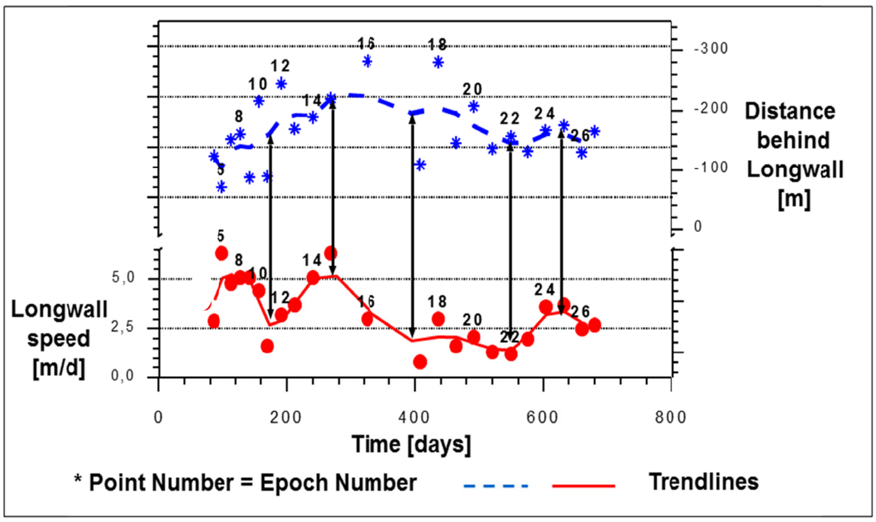


Fig. 4. Position of focal point of impact behind longwall/ longwall speed (Hegemann, 2002)

The focal points are situated about 70 m to 280 m behind the face (Fig. 4). Therefore, the distance behind the front of the face is not constant, but depends on parameters, which have to be determined. These can be following parameters:

– Change of the mining situation,
– Change of seam thickness,
– Change of the mining depth,
– Change of panel speed.

There were no significant changes of the parameters mining situation, seam thickness and depth. But the panel speed is the essential dynamic parameter of the working activities. For a periodic evaluation of the measurements, it is sensible to look at the same periodic panel speed. Therefore, the panel speed during the epochs was averaged out. As a result, the average speed per epoch fluctuate strongly between 0.80 m/d and 6.50 m/d.

The relation between the daily speed rate of the panel and the distance of the focal points to the face shows a qualitative similarity of the two graphs, if a trend line is added (Fig. 4).

It is obvious that the distance of the focal point behind the longwall face is smaller with low speed rate than with higher speeds. Changes of the speed have a very short effect on the position of the focal point of impact. Clearly, this effect occurs at about epoch 11; at this time the panel advanced 600 m (30%).

The curve of the two trend lines in the figure is very similar; the arrows in the diagram illustrate that. Reasons why this effect did not occur previously may be due to the behaviour of the roof strata after starting the panel or the very large differences of the panel speed.

If the focal point of impact changes very often its position relative to the front of the face, this affects significant to the direction of horizontal movements. This is to see in the model of Fig. 5, where the speed rate is low (above) and the distance of the focal point behind the face is about 50 m. In the other case (below) the speed rate is high and so the distance of the focal point is about 280 m. So changing speed means changing between these two situations. As a negative effect the surface points move very unregularly with stronger changes of directions. While an additional dynamic is brought to the horizontal movements (stop- and -go effect), this can cause further damage to buildings.

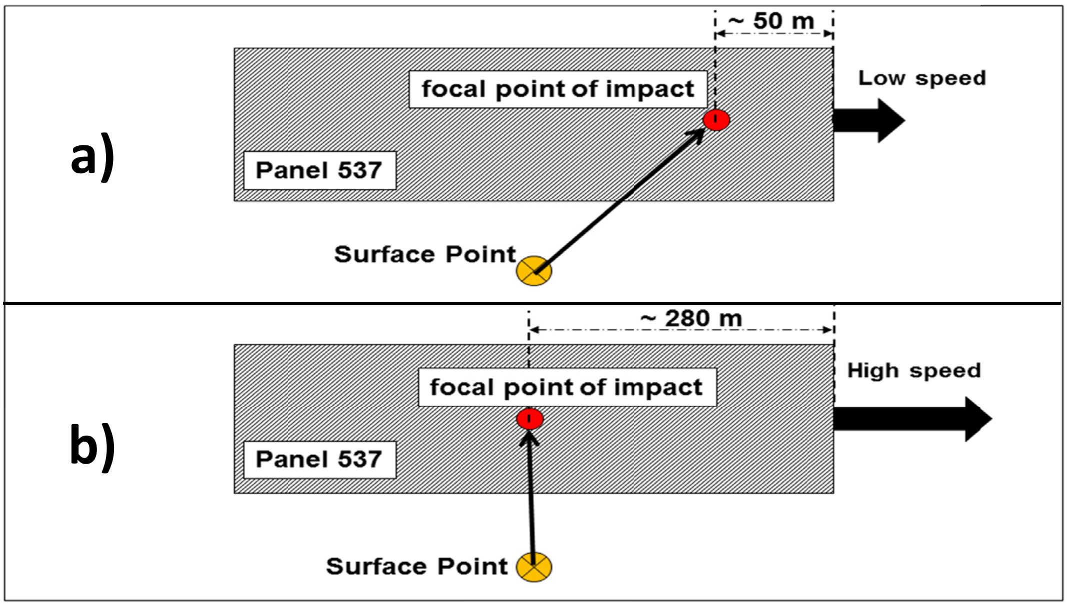


Fig. 5. Influence of longwall speed to position of focal point of impact/not scaled (Hegemann, 2002)

Following conclusions can be made from these studies:

- The horizontal movements are constantly changing their direction and follow the moving focal point of impact.
- The activation of movement potentials from older, neighbouring panels must be included in the calculation of the movements.

- Fluctuations of the speed rate cause an additional change of the position of the focal point of impact. Thus, there is an additional dynamic in horizontal movements (stop-and-go effect), which should be avoided.
- To avoid additional mining damage, it is better to keep the panel speed constant and to minimize operational interruption (continuous operation).

These findings fit into long-term research work in Poland, Germany and China (Sroka, 2009; Jiang Yue, Preusse, Sroka, Jiang Yan, 2017).

4. EC Research Project and Professor Knothe

In the years 1999-2002, when Poland is not yet an EC Member, the Institute IMG PAN attends a EU research project as guest institute. The title of the project was "Reduction of Environmental Impact of Mining-induced Ground Movements" (Co-ordinator Dipl.-Ing. Hegemann).

Five Nations and six research institutes or companies take part in this project (Tab. 1).

The aim of the Professor Knothe´s part project is to clarify the impact of the occasional cessation of face advance on the course of ground movement and deformation. Professor Knothe participates in two working meetings of the Research Committee in Oberhausen and Krakow.

In the following chapters some parts of the Final ESCS Report of Professor Knothe's project is presented (Quotation of the Final Report of EC Research Project "Reduction of environmental impact of mining-induced ground movements", 2002):

– Object of Research

The main objective of the project was to demonstrate the applications of the measuring equipment at the Institute and to study rock mass deformations in the wake of mining operations.

The design of model boxes allows for implementation of boundary conditions reproducing different mining techniques. The model box is filled with a loose medium (sand, tiny glass balls); which is justified by the fact that the distribution of mining operation impacts in such media is very similar to that observed in rock mass.

Tab. 1. Project of ECSC Research Project "Reduction of Environmental Impacts of Mining-Induced Ground Movements") ECSC Contract 7220-PR/035

Company, Institute	Title	Projectmanager
RAG AG, Germany	Development of a dynamic advance calculation method on the theory of stochastic media	Dr. Spielberg
RAG AG, Germany	Classification of surface structures and buildings for sensitivity to mining activities and potentials for protection of them against mining-induced effects	Dipl.-Ing. Pöller
INGENIEROS DE MINAS CONSULTORES S.A., Spain	Improvement in the prediction of subsidence effects in the case of inclined seams mining by the means of the application of empirical methods	Dr. J.A.F. Valcarce, Mr. Lopez
INTERNATIONAL MINING CONSULTANTS LIMITED (IMCL), United Kingdom	Pre-mining structural surveys	Mr. Malcolm
INERIS, France	The influence of the time factor on residual mining subsidence	Mr. Al-Heib
CENTRAL MINING INSTITUTE (GIG), Poland (as guest institute)	Mining induced rock mass movements Classification of surface structures in respect of their strength and possibilities of their protection against effects of mining activities	Prof. Dubiński
STRATA MECHANICS RESE-ARCH INSTITUTE OF THE PO-LISH ACADEMY OF SCIENCES (IMG-PAN), Poland (as guest institute)	Applying model studies to highlight the impacts of mining operations on the rock mass displacements	Prof. Knothe, Dr. Rogowska

In each case, it is roughly the normal distribution and may be used as the starting point for theoretical considerations. The degree of medium compaction may be controlled; thus, one can reproduce the mining operations in rock mass more or less affected by earlier mining operations.

The applications of model tests in implementation of selected mining operations and conditions (those that are difficult to observe in the field and cannot be repeated) are also provided.

– Implementation

Laboratory tests of mining-induced ground deformations employ model boxes, which allows for investigating 2D subsidence and deformations in the vertical cross-section (Fig. 6 a, b).

There is also one model which allows for studying 3D displacements (Fig. 6 c), allowing for observation of surface deformations. The design of the model box is such that one can reproduce various mining techniques as well as phenomena occurring inside the rock mass through the control of slit shifting.

The vital element required for measurements in 2D coordinate system is the model box 80 cm × 50 cm × 4 cm. The front walls are made of glass so the displacements are easy to observe and record. The model box is filled with sand (or with tiny glass balls) up to a certain height. Inside the sand are special markers (measurements points); their position is recorded photographically. The number of observation lines varies, depending on the experiment.

The technique of predetermining the subsidence in 2D models is shown in Fig. 6 a and 6 b. Fig. 6 c presents the box designed for 3 D model testing.

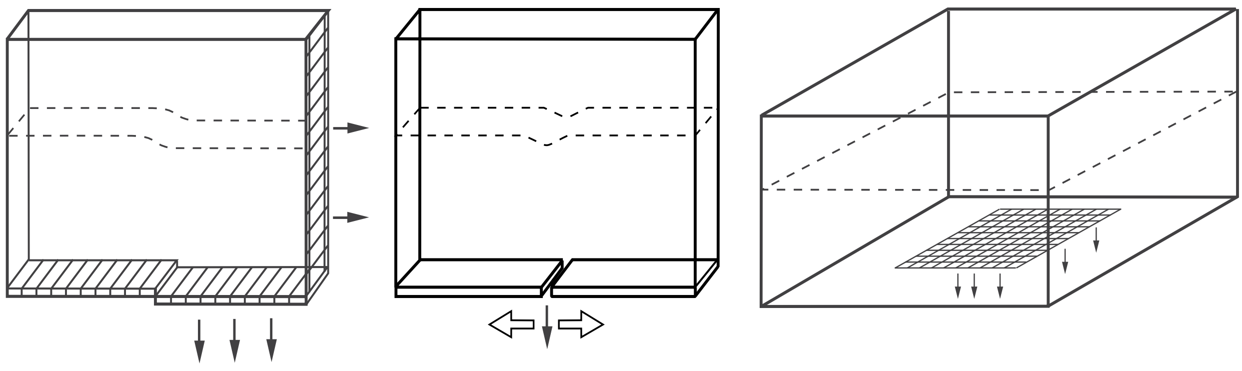


Fig. 6. Setting the boundary conditions (ECSC Contract 7220-PR/035, Final Report 2002)

Depending on the actual task, the displacements can be implemented in several ways.

– 2D model – slit-type trough

When a specified amount of sand is removed through a slit in the box bottom (Fig. 6 b) with the coordinates ($x = 0, z = 0$); the following boundary condition is implemented:

$$w(x = 0, z = 0) = \gamma\delta(x) \quad [1]$$

where:

γ – surface area of thus formed trough

$\delta(x)$ – Dirac function given as:

$\delta(z,x,x0) = 0$ for every $x \neq x0$, while in the point $x = x0$, $z = 0$ it assumes the value (for every ε):

$$\int_{x_{0-\varepsilon}}^{x_{0+\varepsilon}} \delta(z,x,x_0)dx = 1 \quad [2]$$

According to Litwiniszyn, it follows from:

$$\int_{+\infty}^{-\infty} w(x = 0, z = 0)dx = \int_{+\infty}^{-\infty} \gamma\delta(x)dx = \gamma \quad [3]$$

Accordingly, we obtain directly the surface area of thus formed trough. The predetermined Dirac function allows for experimental investigation of direct/basic solutions.

Removing the sand in that manner leads to formation of subsidence troughs, shaped like Gaussian curves while the extremum point lies in the vertical axis passing through the slit. The slit may be positioned at every point in the bottom or it may be shifted at the given rate; while the bottom design (it is covered with a special strip) eliminates the friction between the bottom and the moving sand (Knothe, 1980). The time of slit movement over the whole box bottom may be varied from 8 min to 8 hours.

Slit movements reproduce the advancement of mining operations. Close monitoring of the amount of sand oozing through a slit (i.e. control of drum rotations) allows for reproducing the thickness of the mined-out layer (Fig. 7).

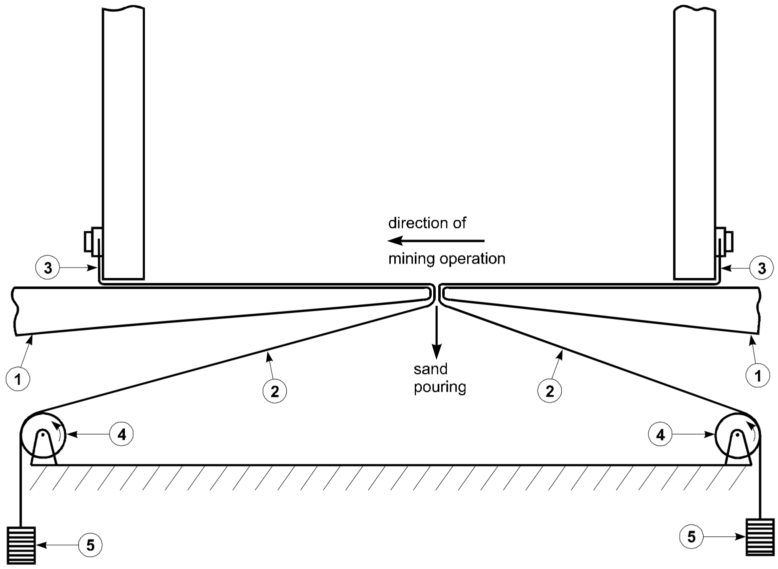


Fig. 7. Model box: 1 – box bottom; 2 – strip eliminating friction between the sand and the Bottom (ECSC Contract 7220-PR/035, Final Report 2002)

– 2D model – threshold troughs

When one half of the model box (Fig. 6 a) is lowered, the boundary condition given by the Heaviside's function is implemented:

$$w(x,0) = \begin{cases} 0 & \text{for} \quad x < 0 \\ w_0 = const & \text{for} \quad x \geq 0 \end{cases} \tag{4}$$

which corresponds to the conditions after a horizontal seam is mined out up to a certain limit. The design of the model box (Fig. 6 a) allows for lowering any box segments to investigate subsidence and deformations for example in the axis of the shaft pillar due to extraction of blocks followed by mining operations starting from the pillar or advancing towards it.

– 3D model

Lowering several from among 100 segments (10 × 10); any configuration is possible, as they are independent of one another (Fig. 6 c).

The displacements are measured through recording the subsequent stages of the experiment on glass plates; then the coordinates of the measurement points are read out in the image processor and fed to a computer database, which allows for calculating the deformation factors for any mining conditions.

Apart from reproducing various mining techniques through setting the boundary conditions, the rock mass behaviour can be also imitated by means of control of the medium compaction. There are several techniques of filling the box with loose or compacted media (Knothe, 1970; Rogowska, 1978; Leśniak et al., 1989). The loose medium imitates the rocks disturbed with earlier mining activities in which cracks and self-subsidence appear in the consequence of earlier mining operations or activation of old goofs.

– Researches and Results

After many models tests the results can be compared with measurements taken in the field:

– Example 1

Experiments with compacted media revealed that the subsidence trough profile is shifted towards the mined-out region (Fig. 8) while the parameter defining the extent of mining impacts is unsymmetrical – they are less significant over the mined-out region and greater over the rock body.

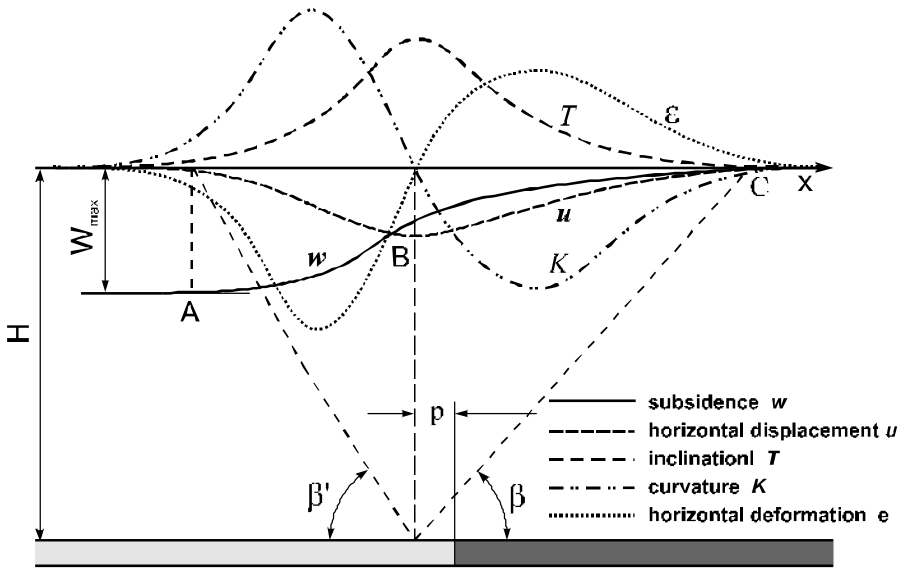
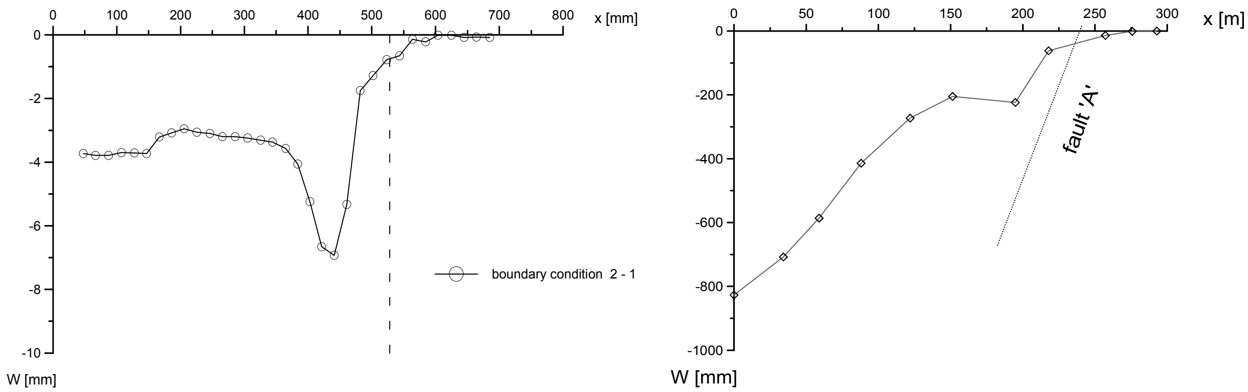


Fig. 8. Subsidences and deformations in the boundary section of a subsidence trough in compacted media

The patterns of horizontal displacements, horizontal deformations, inclination and curvature in loose (non-compacted) media display a certain asymmetry. These observations, confirmed by field observations of trough boundary sections, are of primary importance for prognosticating the negative environmental impacts. It is possible to provide the required medium compaction, depending on the analysed conditions.

– Example 2

Other type of subsidence troughs found in model testing, also verified by mining practice, are increased subsidence in the faulting regions. Model tests reveal considerable subsidence in the region. This anomaly was verified in field studies (Fig. 9).



a) b)

Fig. 9. Increased subsidence in the trough boundary section in the faulting zone; a) in model tests, b) in the mine Centrum (ECSC Contract 7220-PR/035, Final Report 2002)

The boundary section of the subsidence trough in the region behind the faulting zone was also investigated when the mining operations were advancing towards the fault (Fig. 10 a). Increased subsidence in

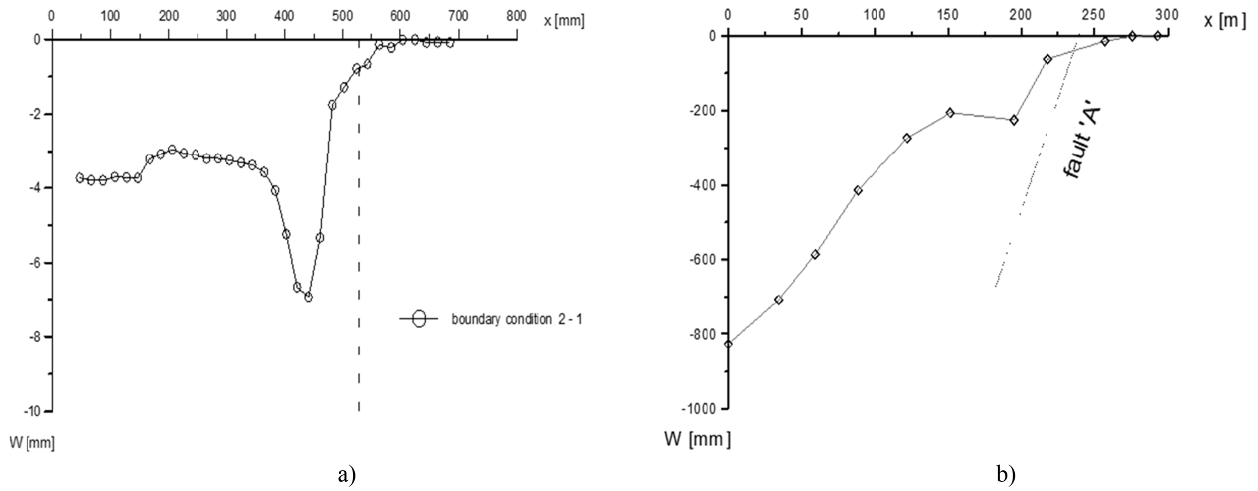


Fig. 10. Increased subsidence in trough boundary section in the region behind the fault; a) in model tests, b) in the mine Paryż (ECSC Contract 7220-PR/035, Final Report 2002)

those regions are also confirmed by measurements taken in the mine Paryż while the seam 510 was being mined (Fig. 10 b).

– Example 3

Using the model box, shown in Fig. 6 b, the tests were run on loose media where the test conditions reproduced the mining operations advancing from the starting region to the limit bound, while the rate of mining operations was varied. For the predetermined subsidence value $w = 4.5$ mm we ran tests where the time of bottom slit movement between the two limit regions would be 35’15” when mining advanced as a low rate and 3’40” for higher rates. Comparison of results of these two experiments leads us to the conclusion that when mining operations proceed at a higher rate, surface subsidence are more considerable. In both cases subsidence over the boundary from where mining operations begin are smaller than near the region where the mining is stopped.

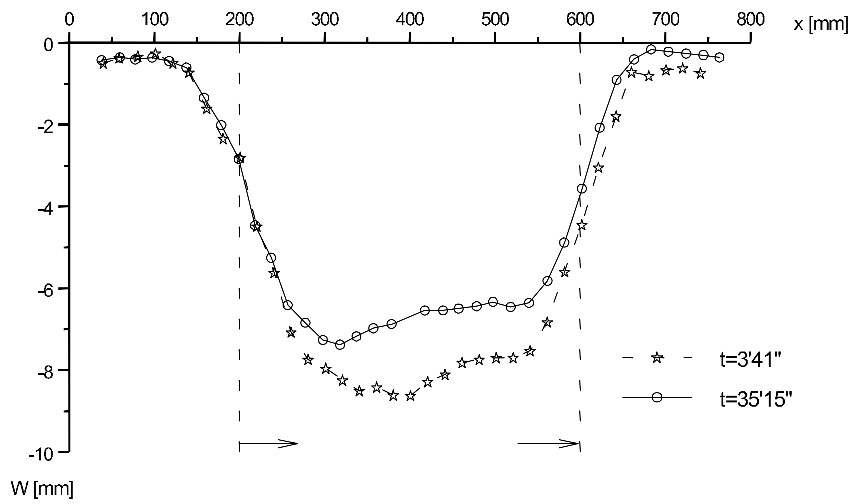


Fig. 11. Experimental subsidence trough over the spots where mining operations began and stopped (ECSC Contract 7220-PR/035, Final Report 2002)

The maximal subsidence is reported near the boundary from where the mining operations begin. This conclusion is of primary importance while designing the mining operations advancing towards or from the protecting or shaft pillars (Fig. 11).

5. Conclusion

Professor Knothe´s academic achievement and particularly his ground movement theory are of vital importance for subsidence engineering in Germany up to today. His scholarly work and that of his students including the author of this article are state-of-the-art in many countries of the world. His scientific contribution over more than 60 years started in the socialistic times, after the fall of the iron curtain he enjoyed full scientific freedom. His engagement for EC Research Projects showed that he was very interested in scientific dialogues between European scientists.

Professor Knothe made a significant contribution to scientific work in Europe with the establishment of "his" Institute of IMG PAN and his activities in international research.

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