ENVIRONMENT PROTECTION

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CLASSIFICATION OF FORECASTING METHODS FOR EARTH'S SURFACE DEFORMATION ABOVE THE SUBSURFACE MINING

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Abstract. *Methods for determination parameters of earth's surface deformation zones were analyzed along with classifications of their manifestations by various criteria which complete and develop existing conceptual estimation of deformation probability by the depth safety criteria.*

Keywords: deformation probability; downwarping; stoped-out area; subsidence trough; surface deformation; zone of rock fall.

1. Introduction

Mining of fossil fuels leads to formation of rocks' interstices. At a certain ratio between the depth and the size of subsurface mining rock movement above reaches earth's surface and it is followed by subsidence. As a result troughs, benches and folds are formed. Rock displacement often reaches significant values, as well as surface layer deformation caused by them. It causes relief displacement, eutrophication, damage or destruction of surface constructions, disturbance in underground waters regime, etc. Surface subsidence takes place because of the rock slides above the stoping of layer with width around 40–60 m. Above-laying rock sheet with depth of 300–400 m smoothly settles without mass folding. Rock mass above it bends and forms subsidence trough of surface in the center of a mine field.

It should be said that ecogeological situation in metallurgical regions stipulated by present intensity of technogenic influence will being worsened due to the following negative factors:

1. Increase of waterlogged and swamped territories mainly in a result of transition to wet conservation of unprofitable mines.

2. Spreading of surface subsidence zones above stopes and resulting watelogging and swamping of large territories (400–500 km^2 of territories are covered by theses processes annually).

3. Increase of negative impact on hydrologic regime of underground water horizons with disturbances in functioning of water supply points and other negative consequences.

2. Analysis of researches and publications

Depending on the quantity, depth and incidence angle of developed deposits, lithologic composition of enclosing rocks, way of strata control and other factors subsidence value can reach 6,7 m (western Donbas). In Krivbas it makes 3–3,5 m, reaching in some cases 5,6 m and more. In Donbas prevailing subsidence depth is about 0,2–1 m (65–70% of the territory subjected to deformations).

The surface of subsidence above mining reaches 50% of the area of each mine field. Taking into account that area of coal mining regions of Ukrainian Donbas is 15000 km^2 it makes 7520–8000 km^2, including about 2500 km^2 in Luhansk region, 4500 km^2 in Donetsk region and about 500 km^2 in Dnepropetrovsk region [Yakovlev et al. 1998]. An intensive subsidence of the Earth's surface in metallurgical regions of Ukraine covers the territory of around 700 thousand ha. For example, in a vicinity of the Lisichansk city there are more than 400 abandoned headings, which result in formation of downwarpings that threaten the city. In Donetsk, in a result of interruption of hydrogeological regime during coal mining, the surface subsidence at underworked fields, including influence of additional static pressure from industrial waste (mine terricones, tailing ponds, etc.) resulted in waterlogging and partial swamping of 1/3 of city territory, in some places downwarpings of earth's surface are even observed [Stolberg 2000].

Such processes are typical for tens of cities and towns of the Donbas (Torez, Horlovka, Pavlograd and others). Thus, surface subsidence at Pavlogradskaya and Horlivskaya minings led to formation of 4 lakes with the total area of 2 km^2 [Stolberg 2000]. In floodplain of the river Samara and its inflows in Krivbas 10 thousand of houses and 340 hydraulic constructions were waterlogged. In a vicinity of mining processing plants (which develop deposits of jaspilites around fields of underground mines) waterlogged area is more than 60 thousand ha; the level of underground waters often increases up to 0,5–2,0 m above the surface.

3. Purpose

Abovementioned clearly shows the importance of studying the problem of engineering-geodynamic broken condition of rock massive by underground minings, development of methods for its forecasting in order to limit negative consequences in space-time coordinates, development of scientifically based and practically proved classification of the phenomenon on a base of generalization of existed analytical decisions for geomechanical tasks and long term surveying observations of processes of formation and development of troughs at different stages of stoping works.

4. Development of deformation probability existing estimation by depth safety criteria

Classification should be based on scientifically perfect criteria and take into account as much as possible factors that determine parameters of troughs' elements, the most important among which are: depth of mining horizon, properties of massive's deposits above stoped-out area, technology of stoping works conduction. At that, attention should be paid how type of the upper leaf of soils that cover parent rocks influences on the character of surface deformation. Movements, which take place in parent rocks, are significantly damped if the above laying soil massive (alluvium) is able to plastic deformation in two forms of earth's surface subsidence:

– Formation of bench;
– Formation of zone of concentrated deformation.

The width of this zone can be determined according to the formula:

$$B = \frac{2H_H}{\text{tg}(45^o - \varphi)};$$

where H_H – capacity of alluvium;
φ – angle of the internal friction.

In tensile phases, i.e. edge portions of subsidence trough cracks appear on the earth surface. They die out with a depth up to the neutral layer (depth about 10 m) and end there. Stratification cracks on the rock sheets appear in places of the biggest tension during mining of steep seam. In places of the greatest stretchings by working out higher-angle layers there are stratification cracks on contacts of layers of breeds, there is sliding a shift on bedding in that part of swally which is over the top half of heading. Presence of different cracks stimulates penetration of underground waters into deeper horizons, changing cardinally the lithologic characteristics of the massive and thus intensifies deformation processes. A particular situation takes place in case when water body bottom or part of riverbed gets in zone of subsidence trough influence. This leads to radical change in hydrological regime, redistribution of hydrostreams (including underground), eutrophication of territories, enhancement of subsidence processes etc. For that matter it is necessary to define more exactly the concept of existence of the so called safe depth H_s, below which rock minings don't cause dangerous deformations on the earth's surface:

$$H_s = K_s M.$$

It is characterized by the safety coefficient K_s, i.e. ratio between depth of bed position to its thickness, causing impact on surface. At that, from the one hand the abovementioned factors of hydrogeological situation change may and should influence significantly on a value of calculated coefficient K_s to increase, but from other hand according to the opinion of some foreign scientists (prof. Kugiel M., prof. M. Chudek others [Chudek et al. 2000]) based on long-term instrumental observations, subsidence and deformation of surface take place above stopings that are located at any depth of mining.

To develop classification based on modeling of massive deformation process above stoped-out area we come from the following assumptions:

1. Medium is supposed to be homogeneous with low tensile strength and constant mass per 1 long meter at every depth independently from overburden stress;

2. Poisson ratio on investigated depths is taken to be constant for the given type of rock;

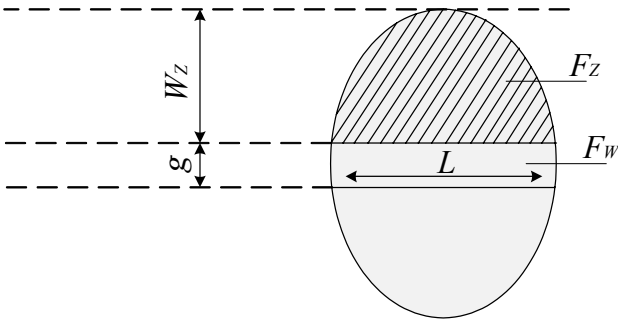3. Zone of rock fall is considered to be elliptical shape.

Zone of rock fall can be expressed by the following ratio:

$$F_Z K = F_Z + F_W \,,$$

where F_Z – area of the part of halfellipse above the stoped-out area;

  K – is fragmentation index;

  F_W – area of the stoped-out area (Fig. 1).

Fig. 1. Caving zone above the stoped-out area:

F_e – ellipse surface;

g – thickness of a bed

The height of halfellipse above the stoped-out area is equal to:

$$W_Z = g \frac{4(K+1)-(K-1)}{2(K-1)} . \qquad (1)$$

Broken ground is solidified with time and index K can decrease to the value 1,1; then caving zone can be approximately in 14,4 times bigger than the height of mining g. While width of the stoped-out area L increases (Fig. 1), the new fragmentation ellipse is forming and it may reach surface (Fig. 2).

If depth H, height $h=g/2$ and Poisson ratio are known, then it is possible to find the value of either length of stoped-out area *(L)* or the boundary head room g, which excludes appearance of subsidence zone on the surface at correspondent ratio *a/b=M* (Fig. 2). The diameter of trough is:

  d=2h$_H$ctgφ+2r,

where *r* – radius (width) of stoped-out area in a layer;

  h_H – depth of caving zone (capping thickness).

One of the estimation parameters for deformation zones and forecasting of surface subsidence is the following index:

$$Z = \frac{H - h_H}{g} . \qquad (2)$$

This ratio allows connecting some probability function $(\varphi)=!!!(Z)$ [Vovk et al. 2007] with parameters of deformation zones and subsidence trough. Table 1 presents estimate indicators of trough formation probability *(P)* at different values *Z*.
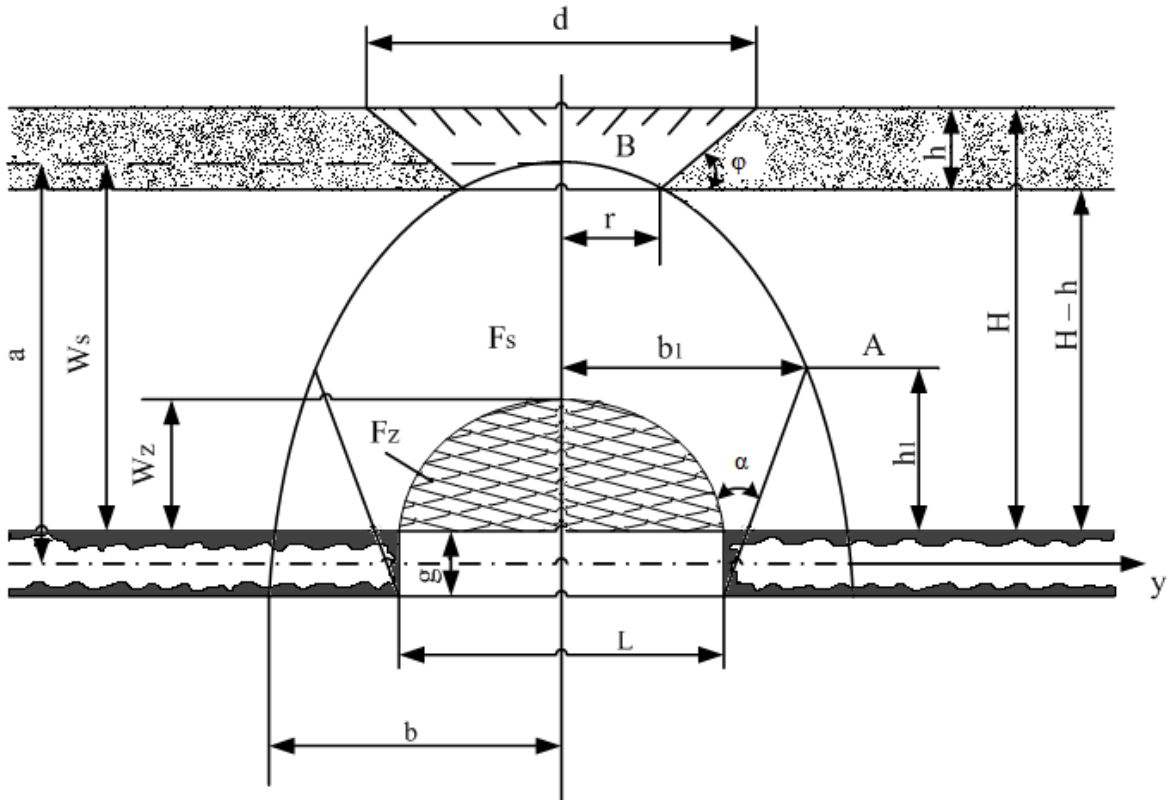
Fig. 2. Form of the caving zone at increase of width of the stoped-out area (α=45°-φ/2)

Table 1. Probability of subsidence trough formation as a function Z

Z	10	11	12	13	14	15	16	17	18	19	20
P	1,0 (0,999)	0,96	0,93	0,9	0,87	0,84	0,81	0,78	0,75	0,72	0,69
Z	21	22	23	24	25	26	27	28	29	30	-
P	0,66	0,63	0,6	0,58	0,55	0,52	0,5	0,47	0,44	0,42	-
Z	31	32	33	34	35	36	37	38	39	40	-
P	0,39	0,37	0,35	0,32	0,3	0,28	0,26	0,23	0,21	0,19	-
Z	41	42	43	44	45	46	47	48	49	50	-
P	0,17	0,15	0,13	0.11	0,09	0,07	0,07	0,03	0,03	0	-

The Table 1 is done on a base of calculations of the function P in a form of probable equation:

$$P = 1,34 - 0,036Z + 0,00019Z^2. \quad (3)$$

Basing on the data in table 1 it is proposed to divide Earth's surface into 4 categories according to the index of its deformation probability.

Category A. The value of parameter $Z > 50$. This means that the height of deformation zone doesn't reach lower border of alluvium, therefore probability of cirques formation is excluded.

Category B. Parameter Z is changing from 30 to 50. Deformation zone reaches borders of alluvium. Probability of downthrows and cirques formation is not high, only 2% of registered cases of surface deformations took place at $Z > 30$. For this category $0,42 > P \geq 0$, deformation is of low probability.

Category C. Parameter Z is changing from 10 to 20. It means that the probability of downwarping is high in a range $10 < Z < 20$ and average in a range $10 < Z < 30$.

Category D. Parameter Z is changing from 0 to 10. It means that caving zone is almost stabilized, function $P = 1$, probability of appearance of surface subsidence deformation is high (correction coefficient is 0,999).

Division according to these categories may be represented graphically in a form of linear graphs in coordinates $g \approx H$ (Fig. 3).
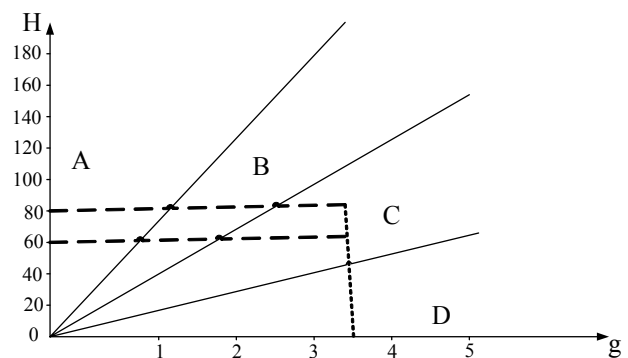
Fig. 3. Distribution of surface deformation according to categories A, B, C, D depending on the value Z

Basing on them it is possible to obtain data, which category of surface deformation danger the given border region belongs to according to certain conditions, defined by formula (2), (3).

Summary height of caving zone and fragmentation:

$$W_{s\,max} = 50g.$$

Parameter of solidification of deformed rocks can change from 0 (for category D) to $W_n > 15$ for category A [Vovk et al. 2011].

Table 2 presents comparing classification according to parameters Z and W_n for 4 categories in order to forecast deformation processes on the surface.

Table 2. Classification of collapse phenomenon probability

Estimation criteria	Categories			
Probability of deformation appearance with discontinuity	A	B	C	D
	$Z > 50$ $P = 0$	$30 < Z \leq 50$ $0,45 > P > 0$	$10 < Z \leq 30$ $1 > P > 0,42$	$0 < Z \leq 10$ $P = 1$
Concentration index	Category			
	A	B	C	D
	$W_n = 0$	$W_n < 5$	$15 \geq W_n \geq 5$	$W_n > 15$
Maximal diameter of deformation within cirque	Group			
	1	2	3	4
	$d \leq 5$	$d \leq 10$	$d \leq 20$	$d > 20$

If the deformation zone of alluvium has conical form, the diameter (*d*) is determined by the formula (Fig. 2):

$$d=2h\mathrm{ctg}\varphi+2r,$$

where *h* – thickness of alluvium;

According to scale index cases of deformation are divided into 4 groups.

Let's illustrate the location of probable danger by graph (Fig. 2) on example. Let the thickness of stoped-out area is equal to *g* = 3,5 m, it is displaced on the depth *H* = 80 m with thickness of alluvium *h* = 20 m.

Then $Z = \dfrac{80-20}{3,5} = 17,2$.

Point *T* on Fig. 3 is located in the range of category B, probability of surface deformation, calculated by formula 1 is equal to *P* = 0,78. Value of deformation in a form of parameter (*d*) of cone or trough-like shape depends on the depth of deposit mining $d=\varphi(H)$, thickness of alluvium $d=\varphi(h)$ and thickness of mining bed $d=\varphi(g)$.

Fig. 4 presents the complex nomogram in order to forecast surface categories by two criteria *Z* and W_n, taking arithmetic mean value d_1. Values d_1, d_2 are diameters as function *H, h* and *g* correspondingly. Point *T* corresponds to Fig. 3. For better understanding of the forecasting method with the help of nomogram, there is a point *T*, which lies according to Fig. 3 in category B with coordinates *H* = 80 m; P_1 = 0,78; *z* = 17,2.

The example of nomogram use: if surface is defined by symbol 1112A, it means that 111 is a value of deformation, which is ≤ 6 mm/m; 2 – is maximal value of horizontal discontinuities of the surface at $d \leq 10 m$; A – is the region where irreversible deformations of solidification have large values.

Let's make an approximate forecasting calculation of deformation parameters according to abovementioned method (Tables 1-3, Figs 2, 3, 4).

The initial data are: *H* = 40 m; *h* =20 m; *P* = 1;

g = 2 m; $W_n > 15$; $Z = \dfrac{40-20}{2} = 10$.

Diameter by factor *H*: d_1 = 4,3 m; d_2 = 6,5 m; by factor h: d_1 = 5,2 m; d_2 = 24 m and by factor: d_1 = 3,5 m; d_2 = 8 m. The average diameter is 8 m (it may increase up to 24 m). The surface can be considered as category 4A.

Surface deformation can take not only cone-shape downwarping, but also scissure configuration, which in a process of mining development gradually takes subsidence trough form with formation of cracks in the main part.

Table 3 represents classification of visible surface deformations stages and degree of danger of surface objects destruction depending on their parameters.

5. Conclusions

1. Forecast of level and character of surface deformations caused by underground minings has a great engineering value. Forecast data allow taking on-time measures to prevent, localize or minimize processes of surface deformation and their average impact on surface objects in a vicinity of mining field.

2. The article describes methods for determination parameters of earth's surface deformation zones. There are classifications of their manifestations by various criteria, which complete and develop existing conceptual estimation of deformation probability by the depth safety degree H_s.

Table 3. Classification of danger degree for surface constructions by the value of visible surface deformations

| Group	Value of measured irreversible deformations			Danger degree for surface objects
	Flat deformations	Linear deformations (cracks)		
	Diameter of deformation zone, *d*, m	Width of scissure *S*, m	Height of fault edge, *h*, m	
1	$d \leq 3,0$	$S \leq 0,05$	$h \leq 0,05$	Do not pose danger for buildings that are insufficiently equipped against insignificant irreversible deformations, or objects that are resistant to reversible deformations, but pose danger to linear constructions (roads, communications).
2	$3,0 < d \leq 9,0$	$0,05 < S \leq 0,15$	$0,05 < h \leq 0,1$	Dangerous for all objects that are insufficiently equipped against insignificant irreversible deformations, and also for equipped but at large deformations of solidification
3	$9 < d \leq 18$	$0,15 < S \leq 0,25$	$0,1 < h_c \leq 0,25$	Do not pose danger only for objects that are equipped properly.
4	$d > 18$	$S > 0,25$	$h_c > 0,25$	Pose danger for all objects.
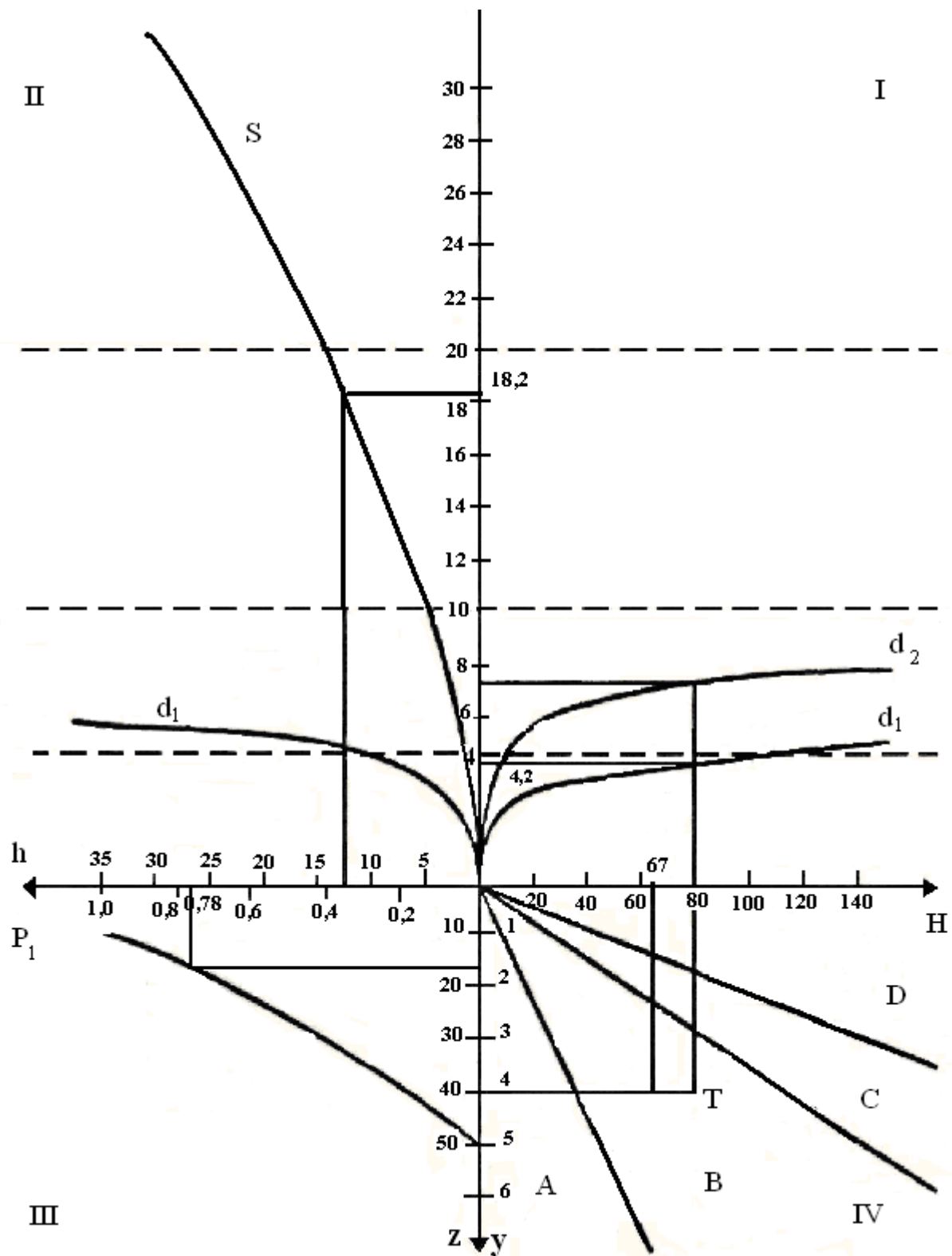
Fig. 4. Nomogram for determination of surface category according to the degree of mining work impact

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Н.С. Ремез[1], **О.О. Вовк**[2], **А.В. Яковлєва**[3]. **Класифікація методів прогнозування деформації поверхні землі над підземними гірськими виробками**

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Проаналізовано методи визначення параметрів зон деформації поверхні землі. Розроблено класифікацію їх проявів відповідно до різноманітних критеріїв, що доповнює та розвиває існуючу концептуальну оцінку ймовірності деформації за критерієм безпечної глибини виробки.

Ключові слова: видобуток вугілля; вироблений простір; зона обвалення; ймовірність деформації; мульда; поверхнева деформація.

Н.С. Ремез[1], **О.А. Вовк**[2], **А.В. Яковлева**[3]. **Классификация методов прогнозирования деформации поверхности земли над подземными горными работами**

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Проанализированы методы определения параметров зон деформаций поверхности земли. Разработана классификация их проявлений соответственно различным критериям, которая дополняет и развивает существующую концептуальную оценку вероятности деформации по критерию безопасной глубины выработки.

Ключевые слова: вероятность деформации; выработанное пространство; добыча угля; зона обрушения; мульда; поверхностная деформация.

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