PREVENTION OF DAMAGE TO HIGHWAYS AND RAILROADS IN MINING AREAS[1]

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Abstract

Roads and railways, a distinctive part of Civil Engineering, when situated in subsidence areas, are subjected to the multiparameter reactions of soil due to subgrade deformation. The essence of technical degradation of such objects due to mining-induced subsidence entail changes in their functional and stability-strength properties. These changes take place within the structural system itself and, also in its subgrade. The linear character of such objects as a highway or a railroad creates a specific type of interaction between the subgrade and the elongated structure. The type of mining-induced contact reactions and the magnitude of service loads determine the operating capability of structures under these specific conditions. The need to maintain the proper geometrical parameters of the system (grade line, slope, superelevation, horizontal and/or vertical curvatures) arises from the necessity to maintain safe and uninterrupted traffic.

The paper is based primarily on the author's broad and lengthy research experience.

Additional Key Words: mining damage, transportation structures, subsidence basin.

Introduction

Underground mining of useful minerals from protection pillars erected for transportation structures constitutes a considerable economic problem for Polish mining engineering.

40% of the total amount of minerals mined in Poland, particularly hard coal, brown coal, metal ores, and other minerals, is extracted in highly industrialized and developed areas. It is estimated that since World War II about 10% ($1.5 * 10^9$ tons) of the total natural resources has been exploited, and the remaining 90% will be subject to mining in the future. It should be emphasized that the rate of mining has dropped during the last several years due to major economic changes that have occurred in this part of Europe. This reduction is especially significant for hard coal; the amount extracted in the 1980's amounted to 240 million tons per year, whereas this year it is only 150 million tons. The dense system of the highway and railroad transportation infrastructure in southern Poland converges with areas in which coalbeds occur in Silesia, which are deposited 100÷1,000 m deep, with global thickness ranging from 5 to 70 m. This creates considerable problems for mining works and also for the effective functioning of transportation systems in the region inhabited by 5÷7 million people.

General Characteristics of Deformations in Mining Site Areas

The classification of mining sites with regard to site utility for development and construction depends on the following: character of anticipated deformations (continuous, discontinuous), type and values of anticipated deformations, type of earthen structure subsoil ground and type of structure. The next part of this paper is concerned with the analysis of deformations occurring with the emergence of continuous, regular subsidence basin with both static and dynamic character.

The basin is characterized by five basic parameters, illustrated in figure .1B:

- subsidence: w [m]
- inclination: $T=dw/dx$ [mm/m] or [‰]
- curvature: $K=d^2w/dx^2$[1/km] (1)
- horizontal displacement: u [m]
- horizontal strain of the subsoil: $\epsilon=du/dx$ [mm/m] or [‰] (loosening - ϵ_L, compacting - ϵ_c); horizontal component of the displacement vector (u) related to the unit of lenght.

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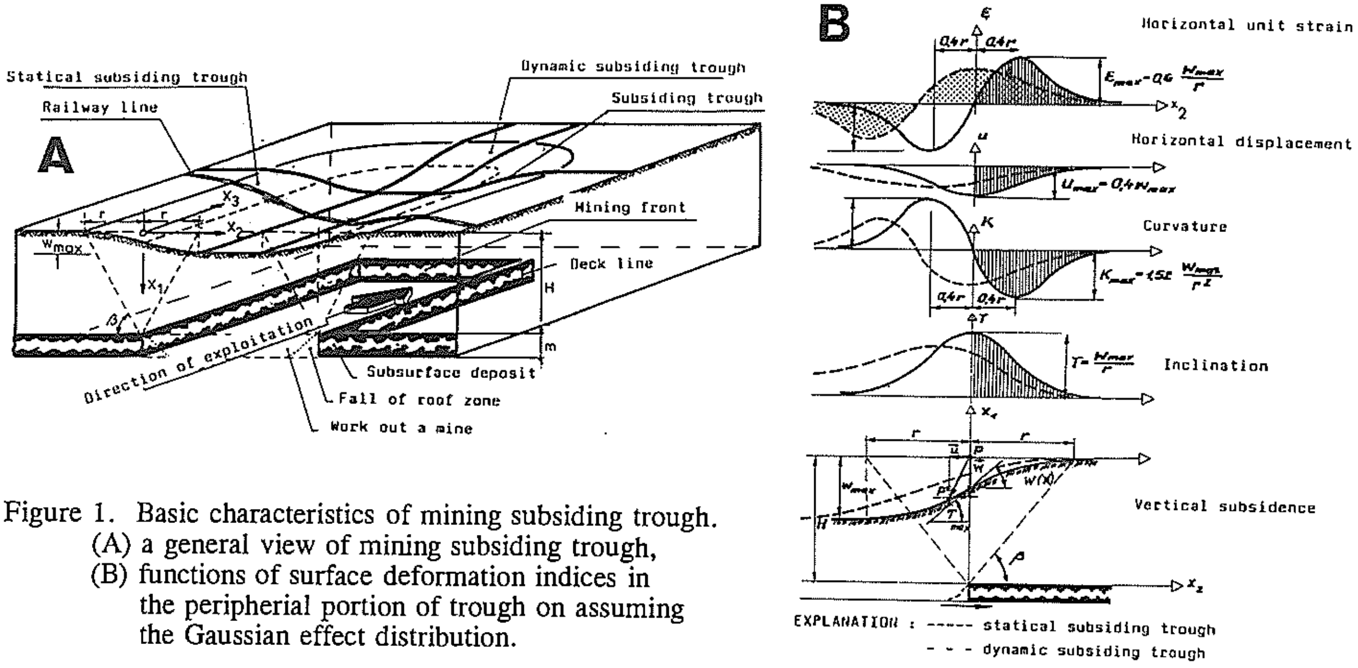

Figure 1. Basic characteristics of mining subsiding trough.
(A) a general view of mining subsiding trough,
(B) functions of surface deformation indices in the peripherial portion of trough on assuming the Gaussian effect distribution.

The analysis of the generalized components of the ground surface deformation of the rock mass zone makes it possible, for modest strains, to determine the unit strain tensor [1]:

$$L^I = \begin{vmatrix} \frac{\delta u}{\delta x_1} & \frac{\delta u}{\delta x_2} & \frac{\delta u}{\delta x_3} \\ \frac{\delta v}{\delta x_1} & \frac{\delta v}{\delta x_2} & \frac{\delta v}{\delta x_3} \\ \frac{\delta w}{\delta x_1} & \frac{\delta w}{\delta x_2} & \frac{\delta w}{\delta x_3} \end{vmatrix} = L^I_\epsilon + L^I_\gamma = \begin{vmatrix} \epsilon_{11} & \epsilon_{21} & \epsilon_{31} \\ \epsilon_{12} & \epsilon_{22} & \epsilon_{32} \\ \epsilon_{13} & \epsilon_{23} & \epsilon_{33} \end{vmatrix} + \begin{vmatrix} 0 & \gamma_{21} & \gamma_{31} \\ \gamma_{12} & 0 & \gamma_{32} \\ \gamma_{13} & \gamma_{23} & 0 \end{vmatrix}; \qquad (2)$$

where

u,v,w, - coordinates of the strain vector in the environment of a given subsoil point.

If adequate substitutions are carried out, in accordance with Cauchy's equation, it is possible to express tensor(2) by means of the components of linear strain ϵ_{ik} and angular strain γ_{ik}(orT_{ik}). By introducing substitutions in the expression of unit tensor rotation L^I_γ and also, by transforming unit strain tensor to a diagonal determinant for three main strains occurring on its diagonal, the following equation may be obtained:

$$L^I = \begin{vmatrix} \epsilon_{11} & 0 & 0 \\ 0 & \epsilon_{22} & 0 \\ 0 & 0 & \epsilon_{33} \end{vmatrix} + \begin{vmatrix} 0 & T_{21} & T_{31} \\ T^*_{13} & 0 & \gamma_{32} \\ T^*_{13} & \gamma_{23} & 0 \end{vmatrix}; \qquad (3)$$

The state described by equation (3) relates to the case where the directions of the coordinates of the frame of reference converge with the directions of deformations of the mining site, which is illustrated in figure 1. Dissymmetrical component tensor L_γ^Idetermines angles of nondilatational strainγ_{ik} in plane (0, x_2, x_3,), inclination angles T_{ik}^* characterizing angular subsoil strains, and site inclination T_{ik} which is most important from the practical point of view. Tensor L^{II} , obtained from second normal derivatives of the unit strain tensor, may also involve the following physical sense:

$$(L^{I})' = L^{II} = \begin{vmatrix} \frac{\delta^2 u}{\delta x_1^2} & \frac{\delta^2 u}{\delta x_2^2} & \frac{\delta^2 u}{\delta x_3^2} \\ \frac{\delta^2 v}{\delta x_1^2} & \frac{\delta^2 v}{\delta x_2^2} & \frac{\delta^2 v}{\delta x_3^2} \\ \frac{\delta^2 w}{\delta x_1^2} & \frac{\delta^2 w}{\delta x_2^2} & \frac{\delta^2 w}{\delta x_3^2} \end{vmatrix} = \begin{vmatrix} \frac{\delta \epsilon_{11}}{\delta x_1} & K_{21} & K_{31} \\ K_{12}^* & \frac{\delta \epsilon_{22}}{\delta x_2} & K_{32} \\ K_{13}^* & K_{23} & \frac{\delta \epsilon_{33}}{\delta x_3} \end{vmatrix} ; \qquad (4)$$

Parameters on the main diagonal of matrix (4) describe the gradients of unit strains in main directions, other quantities characterize the mining site curvatures. Parameters K_{ij} describe mainly the curvatures of subsidence basin.

Classification of Transportation Structures in Mining Site Areas

Transportation structures in mining sites are of a typically linear character. The structure length parameter is much more relevant than structure width parameter, which is important to the static resistance analysis. Other features of these structures are presented in table 1.

To estimate the operating conditions of these structures, the problem of determining their real structural and functional resistance to mining site deformations should be approached. Resistance (usability) is assumed to be the capacity of a structure (or a facility) to transfer mining deformations of the subsoil (displacements and strains) maintaining, at the same time, the conditions of safety and continuous utility, relevant to the original design of this structure. Conclusions drawn from practical experience indicate that every component of a highway or a railroad system, such as subsoil, roadbed, earthen structures, pavement, contact line, drainage systems, engineering constructions (bridges, culverts, retaining walls, etc.), have different resistance to the effects of mining.

Table 1. Classification of structures on mining sites [8]

Basis of classification	**Structure features**		
shape of horizontal view	compact	[✓ linear]	
structure capacity to strain with ground subsoil deformations	rigid	[✓ deformable]	
functional and structural vulnerability to the effects of subsoil deformations	[✓ vulnerable]	not vulnerable	
maintaining conditions of safety and utility	resistant	[✓ partly resistant]	not resistant
occurrence	[✓ common]	rare	

Generally speaking, functional resistance results from structure vulnerability to deformations of road profile and route, changes in values of pavement longitudinal and diagonal inclination, increase of the number of profile curves, changes in horizontal and vertical arch curvatures.The effects of mining are the following: considerably lower speed of traveling, decrease of transportation line capacity, increase of delays and safety hazards concerning transportation systems, increase of noise emission, failure of the patency of drainage systems, technical deterioration of the transportation means and infrastructure, necessity of more investments to enable the functioning of transportation systems. If the allowable value of structural resistance is exceeded, the following consequences may arise: permanent deformation of the roadbed and subgrage (landslide, landslip) track surface and pavement damage (buckling of tracks in the horizontal or vertical plane, uplift or cracks in the road pavement), damage or destruction of bridges, culverts, retaining walls, destruction of technical infrastructure, etc. Transportation structures are characterized by relatively small structural and functional resistance to the effects of mining. In particular, this applies to the basic structural element, that is, railway and road earthen structures in the form of embankments or cross-drifts.

Transportation Structures in Mining Site Areas

The interaction of mining subgrade and structural elements of roads and railways is a complex process. The elements of a technical structure, which constitutes the pavement structure and subgrade, depend on basic ground surface deformation indices in various degrees (3-4). From a geotechnical point of view, horizontal strains of a ground surface exert a decisive influence on the state of stress in the subsoil, especially with regard to loosening strains ϵ_l. They may evoke the following consequences [2,7,9]:

-loss of load capacity in the subgrade zone due to subsoil; softening; fig.2-1.

-loss of load capacity in embankment subsoil or cross-drift; foundation zone (2).

-diagonal deformation of the whole body of the embankment ("bell" cut section) (3), and additional subsidence of the embankment foundation (3*).

-landslide resulting from the diagonal loosening of the embankment subsoil (4) or from subsoil uplift pressure (5).

If inclination T is increased, there is a possibility of the diagonal shift of the whole earthen body of a structure after the tangential stress in the slide zone (C) occurs, irrespective of the permanent change of the slope inclination (B). Considerable rise of the slide height (to 20-30 m) may also be a source of stability hazard due to the need of maintaining the pavement grade line (A).Also, the change in the ground waters level caused by mining site subsidence results in the flooding of the foundation of embankments, which in turn weakens the load capacity of the subsoil and the stability of the earthen structure slopes (figure 2-A).

The factors mentioned above lead to the repositining of the stress and strain components in the subgrade. Horizontal loosening strains ϵ_l will generate the change of the state of stress in the mining subgrade $\Delta\sigma^l_{ik}$. Assuming that vertical strains σ_{11} do not change, the repositioning of horizontal strains is described by the equation:

$$\sigma^l_{ik} = \sigma^*_{22} - \Delta\sigma^l_{ik} = \overline{\gamma}_0 * h^* \begin{vmatrix} 1 & 0 & 0 \\ 0 & (m-1)^{-1} & 0 \\ 0 & 0 & (m-1)^{-1} \end{vmatrix} - \begin{vmatrix} 0 & 0 & 0 \\ 0 & \frac{2G(m+\rho)}{m-1}\epsilon_{22} & 0 \\ 0 & 0 & \frac{2G(1+m\rho)}{m-1}\epsilon_{22} \end{vmatrix} \geq \sigma^{\lim}_{22} \; ; \qquad (5)$$

where

σ^*_{22} - total strain, including the pavement and rolling stock weight

$\Delta\sigma^l_{ik}$ - the change of the state of stress in the mining subgrade

$\sigma_{22}^{\lim}$ - minimum value of horizontal strain $\sigma^{\min}_{22}$ in the total active rankine state

$\overline{\gamma}_0$ - average bulk density of the subsoil, figured from the subgrade level

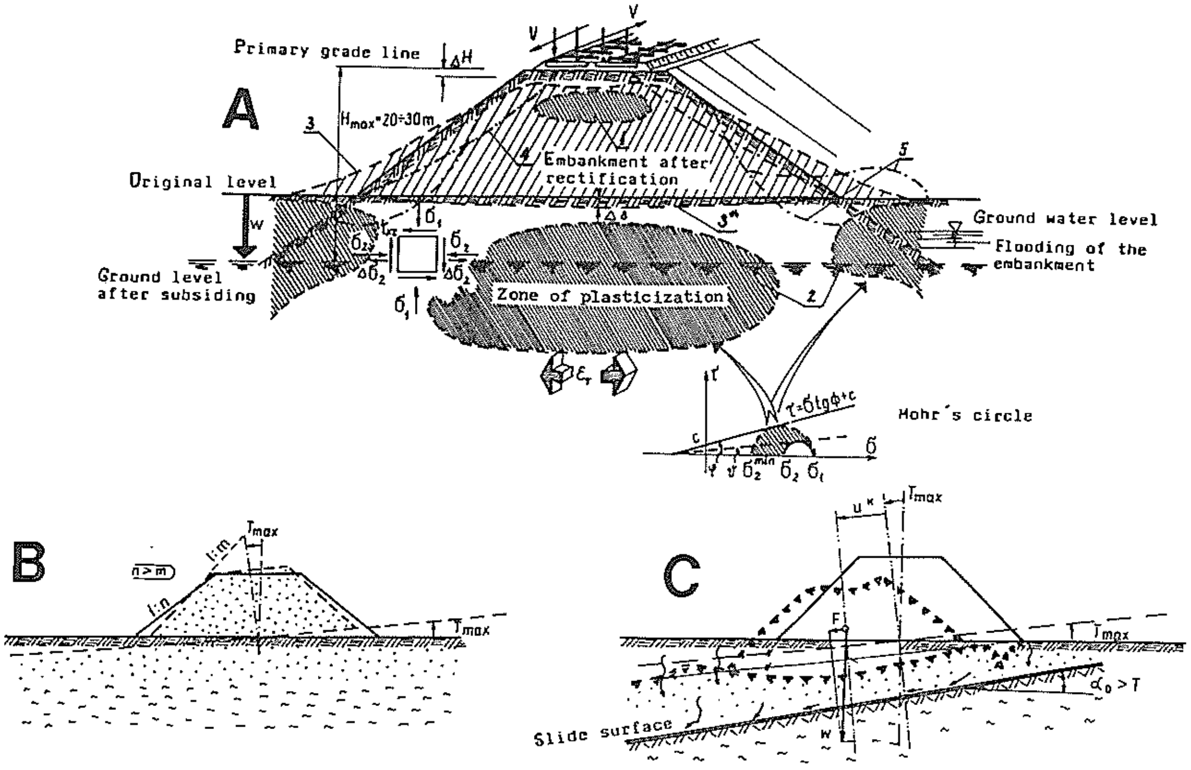

Figure 2. Load capacity and transvere stability of the embankment on mining areas:
(A) typical damages in the embankment and in earthen foundation,
(B) influence of inclination T_{max} ,
(C) influence of sliding on the internal slide surface.

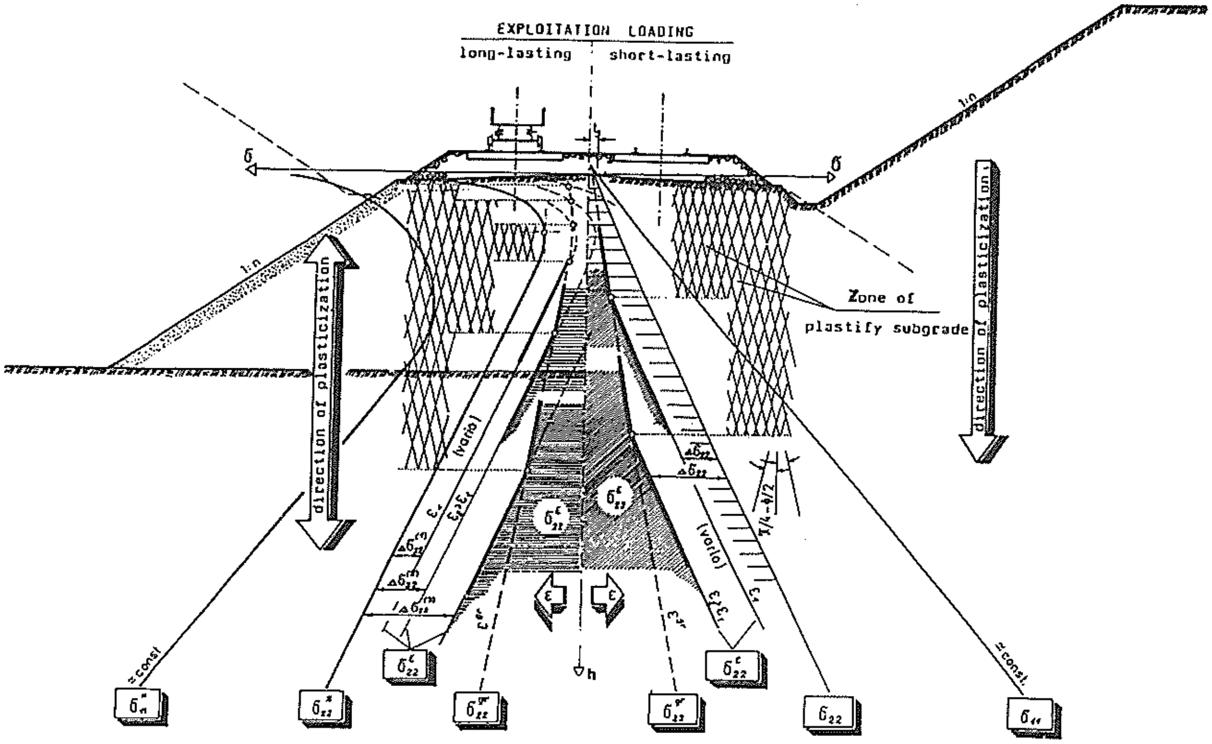

Figure 3. Development of plasticization zones in subgrade on mining areas depending on the nature of operating loads of railway subgrade.

$h^{*}=t_g/\gamma$ - equivalent bed thickness, including the pavement weight
t_g - vertical stresses caused by the pavement weight
$m=1/\nu$ - coefficient of diagonal subsoil deformation
ν - Poisson's coefficient
$G=E_\epsilon\, m/2(m+1)$- subgrade diagonal elasticity module
E_ϵ - subsoil strain module in the mining deformation conditions
$\varrho=\epsilon_{33}/\epsilon_{22}$ - relation of horizontal strains in main directions.

The graphic interpretation of equation 5, based on the theory of boundary states, is presented in figure 3. Figure 3 illustrates the emergence and development of the subsoil softening zones in the subgrade, depending on the principal working load. In the case of temporary loads, the softening zone occurs at the ground surface zone, and it evolves down the subsoil with the rise of loosening strains. For long-term loads, this zone initially occurs in the subsoil (3-4 m deep) and next develops in two directions. The softening of the subsoil is associated with the temporary loss of load capacity, which practically entails the rise of additional pavement subsidence with regard to the subgrade and the whole body of a structure with regard to the subsoil, which is illustrated in figure 2A. Such kinds of subsidence occur irrespective of mining site subsidence "w". Another factor increasing pavement deformations is the permanent loss of load capacity, connected with the interference of horizontal loosening deformations into the physical and mechanical properties of the ground. The result of this process is the long-term loss of compressive strength of the subsoil ground , which is described by the equation [1][2]:

$$\tau_{max} = \sigma_{11}\, tg\Phi_w + \beta(t)\Sigma_w \geq \tau_{min} = \sigma_{11}\, tg\Phi + \beta(t)\Sigma_w \; ; \qquad (6)$$

where

σ_{11} - ordinary component of effective stress
ϕ_w - angle of internal friction of the ground with humidity w
c_s - structural part of ground general cohesion
Σ_w - ground cohesion, caused by water and colloid systems
$\beta(t)$ - coefficient of mining deformation intensity; $0 \leqslant \beta(t) \leqslant 1$.

Results of experiments carried out for many years indicate that horizontal loosening displacements exert an influence on the quick reduction of the structural part of cohesion "c_s " (with $\epsilon_1 > 6 \div 9$mm/m) and on insignificant decrease of the value of primary cohesion. The repositioning of all components of the state of stress in the subgrade is presented in figure 4 on the basis of the disintegrated media theory from the probability point of view. Figure 4A refers to the subgrade that lost its primary load capacity as a result of mining damage. Among many methods of reinforcing and protecting road earthen structures the techniques making use of geosynthetic materials should be considered as most effective [1,3,4].

Mining Damage to Rail Transportation Systems

Rail transportation systems are of great importance to both passenger and goods transport in Polish economic conditions. This particularly applies to railways and streetcars in the District of Silesia, an area influenced by intensive mining damage caused by the operation of more than 60 mines. About 30% of all district rail lines (700-1,000 km of lines), with load capacity of 45 milion Mg/year, are situated in the zones of direct influence of underground mining. The average subsidence of many lines and stations ranges between 5-15 m, with intensity reaching the range 0.5- 1.5 m/year. The District of Silesia constitutes only 4% of Poland's total surface area, but about 50% of home goods transport and 40% of home passenger transport falls to Silesia. Failure of the elements of railway lines on mining sites increases three to four times more in comparison with lines in other parts of the country. The resulting operational inefficiency of transportation systems constitutes a serious technical and traffic problem.

Streetcar lines in Silesia are 370 km long, which is 15.5% of all Polish streetcar lines. The average speed of travel is not greater than 30 km/h due to intensive mining influence, including discontinuous deformations in the form of pits, crevasses, and cavings. So far, subsidence of the 15% of lines has reached 0-6.5 m. By the year 2010, the rate of subsidence will have reached 6-8 m for 30% of the lines. Also, about 40% of all engineering structures

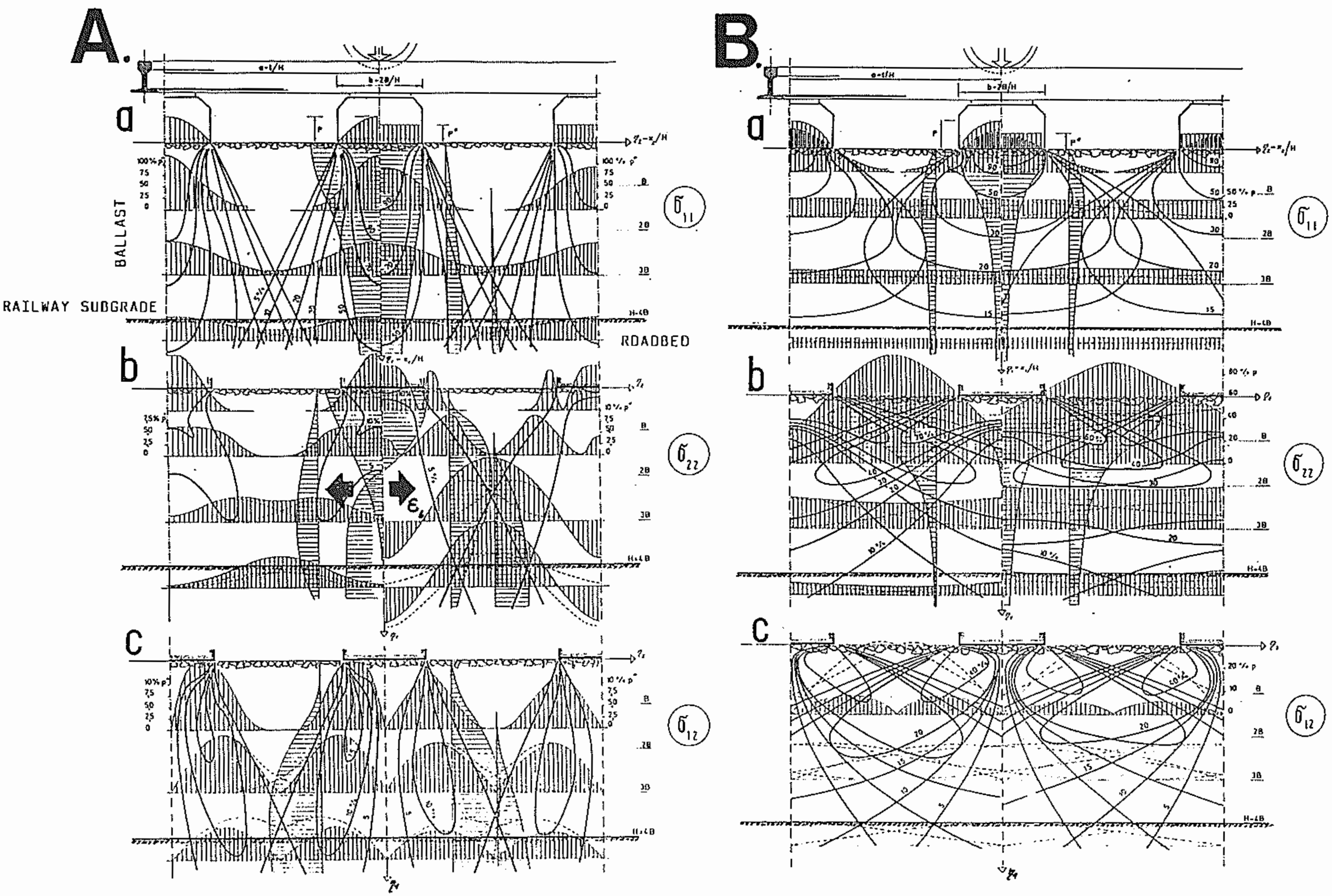

Figure 4. Components of stress state in homogeneous subgrade subjected to horizontal unit strain:

(a) vertical stresses and their isobars,
(b) horizontal stresses and their isobars,
(c) shearing stresses and their isobars,
(A) with influence of horizontal unit strain on mining subsiding area,
(B) without mining damages.

is exposed to intensive influence of mining damage.

The influence of ground surface deformations entails changes in the form of tracks in both route and profile. Ground subsidence causes changes in line profile, which in turn limits the maximum train weight allowable. Because the longitudinal profile inclination of a line is a sum of the primary track inclination"i" and of the profile inclination of mining subsidence basin "T", the allowable value of line inclination (for stations $i_{max}=0.5\text{-}1.5‰$, for lines of I/II/III category $i_{max}=6/12/20‰$ respectively) is exceeded in some line segments. These deformations are followed by changes of track tilt, warping, unacceptable increase of horizontal profile curves, considerable horizontal displacements of railway axes, variable curvatures of horizontal arches, and transition curves.

Prevention of mining damage consists of recommendations for mining to be carried out by means of long and continuous working front, perpendicular to track axes (figure 1).
Preventive treatment of structures is focused on minimizing the range of essential leveling works. In practice this means that tracks are not lifted to their primary grade line. The types of grade lines are the following (see figure5):
- primary (designed) grade line, before the time of mining subsidence occurrence (L_1),
- preventive grade line, taking into account the anticipated subsidence that secures continuous and safe traffic of railway vehicles (L_2),
- temporary (transitory) grade line, entailing the time of subsidence occurrence and also intervals in the successive stages of subsidence (L_3),
- permanent grade line, this is the ultimate grade line, taking into account the anticipated subsidence in relation to primary grade line (L_4).

Preventive grade line can be applied in designing new railways or modernizing railways of special importance. Permanent grade line can play a part in reducing the range of essential leveling works and investment necessary for their execution. The general principle of transportation systems protection is the proper coordination of mining and civil engineering preventive techniques applied to long railway line segments and stations, together with railways junctions. Experiments carried out by the author of this paper indicate that the elastic flexibility coefficient concerning the railroad tie subsoil is reduced, as a result of horizontal loosening strains, by the value:

$$\Delta C_{\epsilon l} = C_0\,(1-\alpha_L^{4/3}); \qquad (7)$$

where

$C_o=p/y$ - output value of the elastic flexibility of the railroad tie subsoil
(p - stress in railroad tie foundation, y - subsidence)
α_L - coefficient of variable compressive module of the loosened ($0 \leqslant \alpha_L \leqslant 1$) subsoil [1,5].

The influence of parameter C on the flexure stress of rail σ and on the deflection value is expressed by the equations:

$$\sigma=\Phi_1\, C^{-0.25} < \sigma_{permis}\,; \qquad (8)$$

$$y=\Phi_3\, C^{-0.75}\,; \qquad (9)$$

$$\Phi_1=P/4W(4EJ/b)^{0.25}\,;\ \Phi_2=0.5Pl(4EJ/b)^{-0.25}\,;\ \Phi_3=\Phi_2(bl)^{-1}\,; \qquad (10)$$

where

EJ - rail flexural rigidity
W - index of rail flexure strength
b - railroad tie width (equivalent)
l - railroad tie spacing
P - railroad tie load force
σ_{permis} - allowable value of rail steel flexure stress.

Site investigation results determined the value of coefficient $5 \leqslant C_\epsilon \leqslant 15$ MPa/m, due to cyclical railway stock operation (fatigue), the allowable value of flexure stresses may be exceeded: $\sigma_{real} \geq \sigma_{permis}$. The cracking of rails and turnout elements occurs more and more often. In Silesia, the number of such cracks is five to eight times greater than in other parts of Poland. Figure 6 illustrates results of calculating flexure stresses for conventional rail surface structure elements, for values of coefficient C measured before (C_0 = 130 MPa/m) and after ($C_\epsilon \cong 3$MPa/m) mining influence occurred. It should be pointed out here that the number of flexure stresses in rails increases with

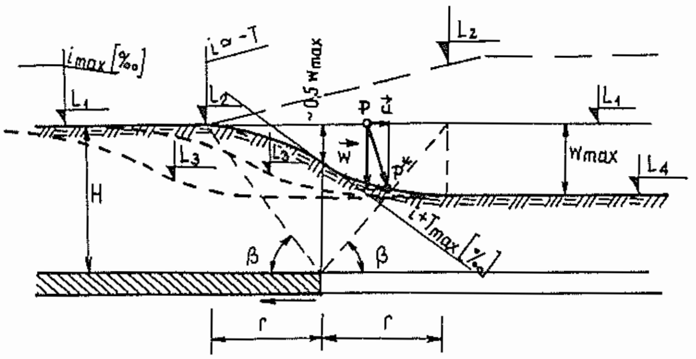

Figure 5. Types of grade lineas on mining subsidence areas.

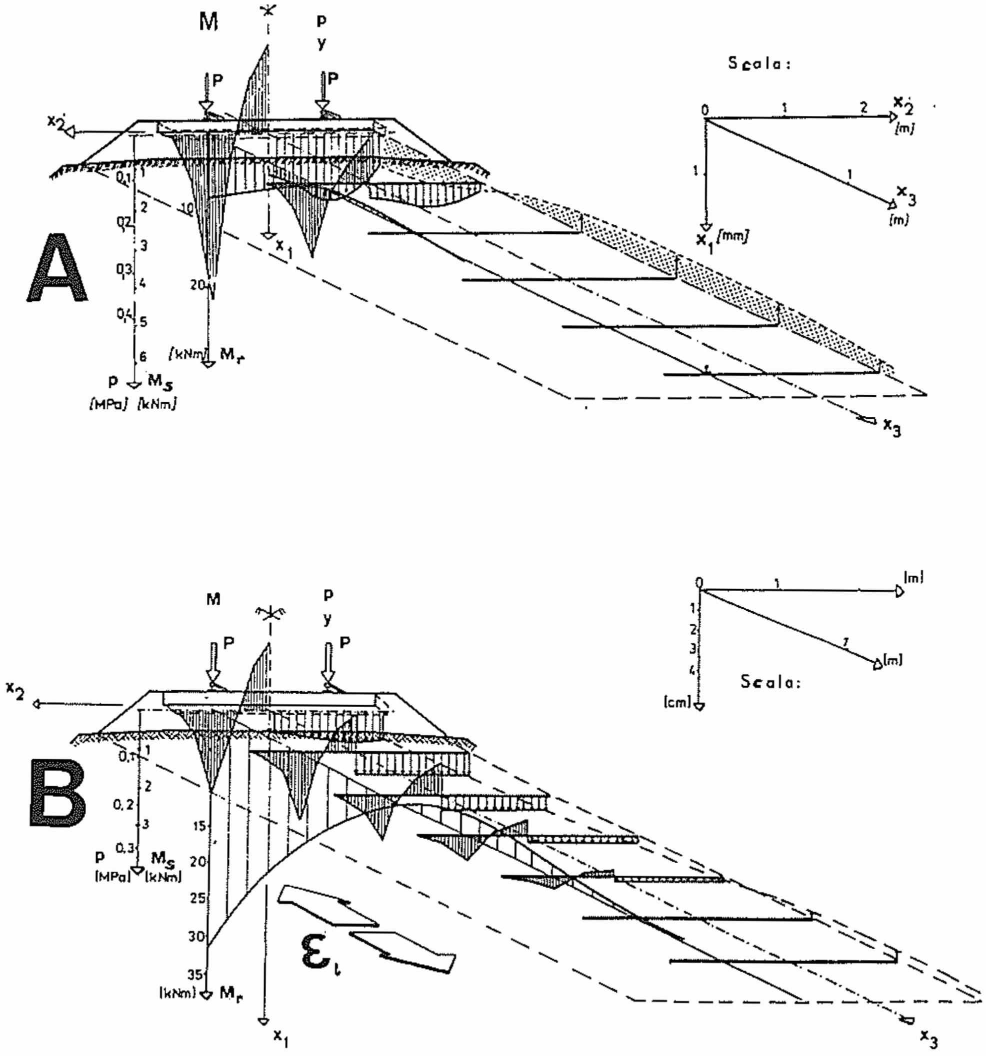

Figure 6. The effect of quasi-static loading of track structure by a single axle of wheel set on its elastic strains, bending moments in rails M_r and sleepers M_S, and a distribution of normal contract reactions "p" in the basic of track layer framwork

(A) on nonmining grounds for: C_0 =130 MPa/m, track structure R-49, load P=98kN,

(B) on mining ground for C_{el}=3 MPa/m.

the reduction of contact stresses in railway tie foundations. Also,rail surface deflection rises,together with the number of railway ties transmitting the external influence.

Mining Damage to Roads

In Silesia the road transportation system is the densest and busiest in Poland (60 $km/100\ km^2$). More than 50% of district roads are influenced by mining damage, and the average occurrence of subsidence ranges within 1÷10m. In some given segments, subsidence may reach the range of 20-30 m in the future. For some internationally important roads, deformations with the following parameter values are anticipated: $T > 15mm/m$, $\epsilon = 9mm/m$, $R = K^{-1} = 4km$. The actual protection of roads in comparison with railways is in a considerably worse state. There are no generally accepted procedures for the execution of mining underneath the roads and, in addition, there are no proven methods of increasing road resistance to the effects of mining.

The mechanism of the occurrence of mining damage in the subgrade may be assumed to apply to roads. Damage to road pavements indicate that structures vulnerable to strains of rigid pavement show better resistance than those that are less vulnerable. Changes in road geometry in route and profile are particularly disturbing, for example: short,local vertical irregularities of surface (pavement bulging), pavement gradation and cracking, loss of the patency of drainage systems, numerous damages to engineering structures such as bridges, overpasses, trestle bridges, culverts. Discontinuous deformations in the forms of crevasses and pits are particularly dangerous, together with the paraseismic influence of the rock mass. In such conditions, roads are becoming less functional and traffic less efficient.The resulting losses of time and energy decrease the economic parameters of roads situated in mining site areas.

Summary

The synthetic analysis of the causes of mining damages occurring in structural elements of roads and railways presented in this paper is based on years of practical experience in this field and also on theoretical analyses of problems explaining the mechanism of the observed damages and the inefficiency of transportation systems. Mining deformations considerably reduce the structural and functional resistance of roads and railways and often create serious hazards to their safety and utility. The resulting damages and defects of pavement and subsoil should not be allowed and therefore require adequate preventives and repairs. The damage reduces the safety of travel, pavement live, and often changes the geometry of roads and railways to the degree that makes effective functioning of traffic virtually impossible. The only possible guarantee of the effective protection of transportation systems in areas influenced by underground mining is the coordination of mining and civil engineering protective techniques.

Literature Cited

[1] Kłosek K. 1988. Effect of mining foundation strains on a cooperation of subgrade with a track structure. Proc. Silesian Technical University, vol.66,p.160.

[2] Kłosek K., Graftiaux H. F. 1982. Quelques problemés concernant la construction d'ouvrages d'art en terrain d'exploitation miniere'. Industrie Miniérale - les Techniques, France, Août-Sept. p.349-359.

[3] Kłosek K. 1992. Efficiency of geosynthetic strenthening of railway bed in conditions of dynamic reactions of vehicles - Field Tests of "SFCM" Prototype. Proc. of the Int. Symp. on "Applications of Geosynthetic Technology", INA-IGS, Jakarta S.I p.7-12.

[4] Kłosek K. 1992. Prototype of Railway Bed of "SFCM" Type with Geotextile Undersleeper Containers - Laboratory Tests. Proc. of the Int. Symp. on "Applications of Geosynthetic Technology", INA-IGS, Jakarta. S.I p.13-17.

[5] Kłosek K. Graftiaux M.F. 1986. Interactions des foundations des ouvrages d'art et du sol d'assise en terrain d'exploitation minieré. Industrie Minérale-Mines et Carriéres-Les Techniques, France, Juin. p.283-292.

[6] Kłosek K. 1993. Contemporary Mathematical Models of the Subgrade in High Speed and Great Axleload Conditions. The 9th Int. Science. Conf. - Univ. of Transport and Communication in Žilina, Slovac Republic, p.103-110.

[7] Kwiatek J. 1993. Some problems of geotechnics on mining areas. Polish Acad. of Sc. Katowice, p.127.

[8] "Śląsk" Publisher. 1980.Protection of the surface before mining damages. p.976.

[9] Rosikoń A. 1979. Transport on mining damages areas. WKiŁ Warszawa, p.315.

[10] Szumierz W. 1980. Stress analysis of linear construction under influence of the horizontal deformation of mining subsoil. GIG Katowice, p.253.