EXTREME IMPACT OF UNDERGROUND MINING ON LINEAR TRANSPORTATION STRUCTURES[1]

by

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Abstract: The paper is focused on the discussion of two separate cases of unique mining works conducted underneath important transportation routes. Placer ore deposits were worked under the railway line of highest technical standard. At the same time, for 100 years the line has been subjected to multi-stage mining impact, exerted by the activity of two neighboring hard coal mines (case I). Apart from the threat of discontinuous deformations and tremors, the land surface has already subsided by 20 – 25 m totally. The problems involved in maintaining the line in operation are discussed.

Case II concerns a possibility of building and operating a continuous rail track in the zone of placer zinc and lead ore excavation. Methods of measuring the axial forces in the track surface are presented, to prevent surface buckling caused by the combined impact of mining and thermal forces

Additional Key Words: mining damages, slope stability, axial forces, stress measurements

Introduction

The impact of underground mining works conducted for over 100 years, as well as of planned roof caving coal excavation, on the efficient performance of main railway line are discussed in the paper. The line in question (case I) is located in Southern Poland (since 1880), in the area of Bytom station. The case involves extreme and detrimental impact of underground mining on the railway infrastructure, especially on the subgrade.

Efficient performance is understood as continuous and safe operation of the railway line as well as durability and reliability of its structural components functioning in the conditions of completed and planned underground mining works.

Another example of unique activities (case II) involving surface protection is the continued excavation of zinc and lead ores at shallow depth (~80 m) conducted under the railway line in continuous operation. This track surface has a continuous (joint-less) structure, which is particularly sensitive to increased additional compression forces caused by horizontal compress deformation of the mining subsoil. Results of the measurements of the continuous rail track, including the axial forces measured by means of non-invasive methods are presented.

In both cases, continued mining activity is a result of economic, technical as well as social aspects.

If the mining works were discontinued a rich deposit would be lost, which would result in making a part of the miners redundant. The mining and civil engineering protection works minimize the damages on the surface, protecting, at the same time, the operational safety of linear structures such as railway lines, pipelines, power lines.

Technical characteristics of railway line

Required technical conditions and parameters

The discussed double track main railway line (case I), among other requirements, should meet the following technical performance parameters:

- maximal speed $120 < V_{max} < 200$ [km/h]
- maximal speed $80 < V_t < 120$ [km/h] for freight trains
- allowable axle load $P < 221$ [kN]
- gradient should not exceed $i_m < 1.5$ ‰ in the vicinity of station tracks.

As far as the subgrade is concerned, the most important requirements include:

- appropriate strength, i.e. load-bearing capacity and stability;
- values of permanent stains and elastic strains caused by dynamic excitations should not exceed the allowable limits;
- invariable shape and dimensions of the subgrade, irrespective of the mining impact.

However, it is the subgrade strain parameter that is of crucial importance; its minimal value on the

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track structure level should meet the following requirement:

$$E_2 > 120 \text{ [MPa]}$$

where:

E_2 - is the secondary subsoil modulus of elasticity. In the course of horizontal deformation of the land surface modulus of elasticity is significantly reduced (Klosek 1995/96), which affects the load-bearing capacity of the subsoil of transportation and other engineering structures.

Actual technical parameters of the railway line

The line has a conventional joint track structure, consisting of R49 type rails which are 30 m long, mounted on wood railroad tie with intermediate K type fix. The track frames rest on break-stone ballast. The general technical condition of the track structure is satisfactory.

The contrast between the basic technical requirements laid on railway structures and the actual technical parameters of the discussed railway line indicate the scale of degradation of the overall linear infrastructure.

The most essential parameters determining this state of degradation include:

- Long- lasting land subsidence reaching the total value of $\Sigma w = \sim 20 - 25$ m (!);
- Increased actual gradient to 20.9 ‰, which results in many limitations to the efficient operation of the line and its station tracks;
- Horizontal displacement of the track axes (so far straight) and turnouts by $u = \sim 2.5$ m;
- Necessity of limiting the speed of trains to
- 20 /30 km/h;
- Subgrade hazard involving the loss of its load-bearing capacity and stability.

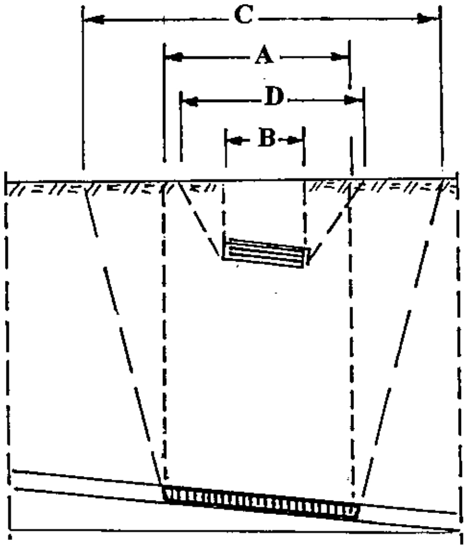

Fig.1a Vertical cross-section of the mining areas A) border of the coal bed area, B) border of the ore deposit area, C) range of the influence of deep-level coal mining, D) range of the influence of placer ore mining (case I).

Undoubtedly, there is a direct cause and effect relation between the above mentioned phenomena and intense mining works with roof caving conducted (especially after 1980s) in the zone of the railway protection pillar, Fig.1a.

Due to underground mining, the subsidence of the gradeline in the last 40 years reached several meters locally, at both sides of the railway line. The total seam thickness at the western side (Coal Mine I) was 27 –30 meters, whereas at the eastern side (Coal Mine II) 33.7 – 47 meters. The superposition of the impact of multiple mining works with roof caving method resulted in total land subsidence in the range of 20-25 m at km 21.0, during the period of 100 years.

Such considerable range of land subsidence is a consequence of long-lasting concentration of mining works conducted under the track and under the road[1].

The works involved roof caving, while simultaneously abandoning other excavation works in the neighboring areas. As a result, the surface gradients have been exceeded, compelling the continual need to increase the height of embankments.

Measurements and field observations of transportation structures conducted for successive years indicate that the failure rates of all structural elements of the subgrade and track structure in mining areas are 3- 4 times higher than the number of damages occurring in other lines of similar load and structural parameters, but operating elsewhere. Thus, the transportation structures located in mining areas need additional protection and maintenance measures, as well as special engineering solutions.

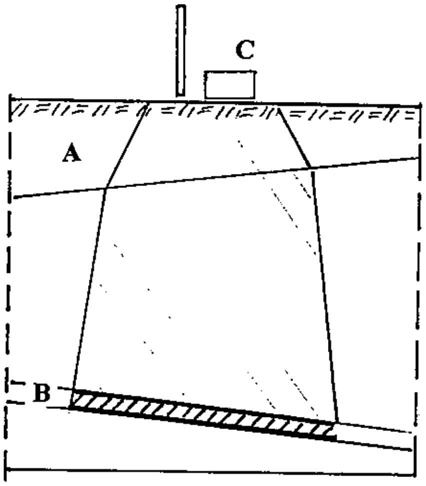

Fig.1b Protection pillar for the land development A) Quaternary, B) coal bed, C) land development

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[1] The two neighboring mines have already extracted their coal mine from 30 seams.

In practice, nearly all the geometric parameters of the railway track have been subjected to the mining impact, leading to increased malfunction and necessity of considerable speed limits for trains, which, in turn, results in substantial financial losses for the carrier.

The infrastructure elements that are exposed to most serious hazards include earthen structures constructed in the form of multi-level embankments (Kłosek 1999).

Increased height of the embankments, under the conditions of tensile strains ε (horizontal loosening strains mm/m. or %o) of the subsoil occurring in the direction perpendicular to the route axes, combined with low load-bearing capacity of the subsoil, pose a fundamental threat to the load-bearing capacity and stability of the subgrade.

The factors that further increase this threat include:

- Migration of the waters crosswise the embankment and its inundation at both sides; transient migration of the ground waters may lead to piping effects in the subgrade;
- Estimated increased diagonal inclination (in the plane perpendicular to the track axes)of the land due to asymmetrical mining, leads to more intense landslide effects pushing the embankment along the subsidence trough slope;
- Propagation of the dynamical forces induced by the mining impact (bounce resulting in para-seismic effects in the form of horizontal accelerations, see Fig.2) and vibrations from the track structure to the subgrade transmitted by passing trains.

The strength of the subgrade is determined by the local soil and water conditions.

Due to a dynamic character of the land surface deformations (Fig.3), the hydro-geological conditions of the subsoil are subject of constant change.

The load-bearing capacity of inundated subsoil is significantly reduced. This results from lowered internal friction angle and soil cohesion, even by 80 %. Another factor that contributes to reduced load-bearing capacity of the subsoil are tensile strains (Kłosek 1995) .

Assessment of Planned Mining Works on Railway Infrastructure

Assessment of the impact of completed as well as planned mining works in the zone of the protection pillar of the railway line.

The projected mining activity concerns working a deposit of convergent protection pillars of two coal mines, the boundary edge of which is the Bytom- Tarnowskie Góry railway line.

The concentration of mine seams in relation to the track (Table 1) has caused the superposition of the surface deformation parameters, unheard of in any other mining areas, especially as far as subsidence and inclination profile are concerned

Additionally, the discussed area also contains the boundaries of two already closed- down zinc and lead ore mines (Orzeł Biały), which worked placer deposits with roof caving.

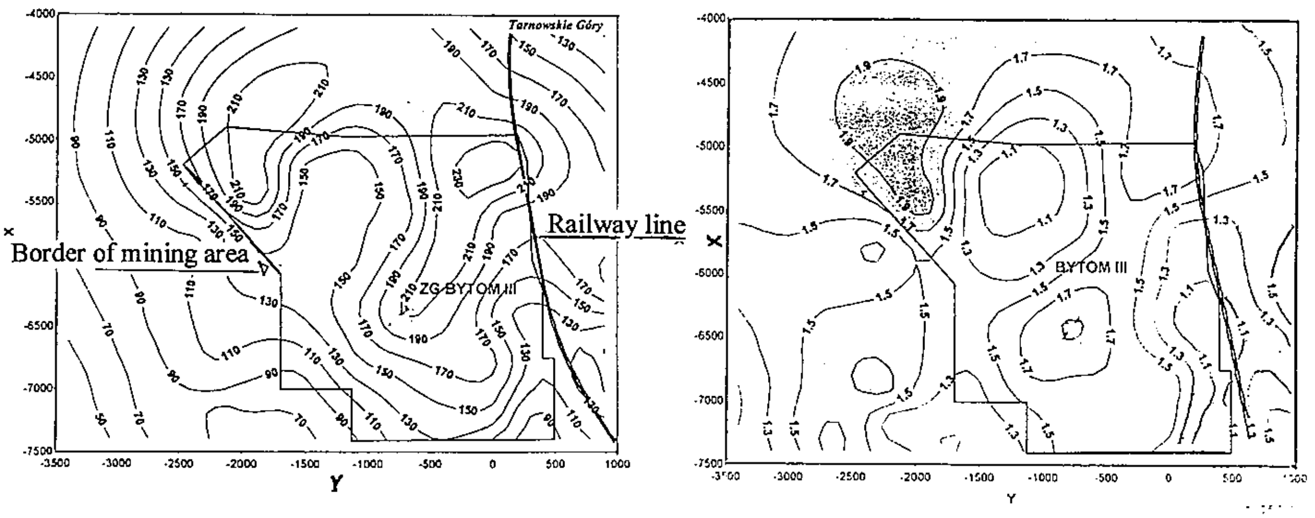

Fig.2 Propagation of the dynamical accelerations induced by the mining impact

A) Map of the maximal accelerations of soil vibration

B) Coefficient of reinforcing vibration accelerations

Table 1a Parameters of coal seams in Coal-Mine I worked in 1939-99
in the direct vicinity of the railway, or directly underneath it

Coal bed No	***Thicknes of seams [m.]***	***Depth [m.]***	***Inclination of layer [°]***	***Time [years]***	***Method of mining***	***Location of coal seam [km]***
1	2	3	4	5	6	7
4o6/4	1.3-1.4	340	3 – 10	1939-41	roof caving	20.5-21.7
408/2	1.4-1.7	440	3 – 10	1954-64	roof caving	20.9-21.7
414/1	1.7-2.0	520	3 – 10	1965-69	roof caving	20.3-21.5
414/2	1.6-1.7	525	3 – 10	1965-67	roof caving	20.9-21.7
414/3	1.6-1.8	530	3 – 10	1967-70	Roof caving	20.9-21.7
418	1.7-2.1	640	3 - 10	1971-75	roof caving	20.0-21.7
419	1.9-2.2	660	3 – 10	1975-78	roof caving	20.0-21.7
501	2.8-3.2	700	3 - 10	1969-86	sand filling	20.0-21.5
507	3.5-3.8	810	3 – 10	1980-85	roof caving	20.1-21.7
509wg	2.5	820	3 – 10	1986-88	roof caving	20.5-21.7
509wd	2.2-2.8	820	3 – 10	1991-94	roof caving	20.8-21.7
510wd	2.4	845	3 – 5	1987-92	roof caving	20.2-20.8
510wg	2.4	840	3 – 5	1996-99	roof caving	20.8-21.3

Sum : **27-30m**

Table 1b Parameters of coal seams in Coal-Mine II worked in 1898-83
in the direct vicinity of the railway, or directly underneath it

Coal bed No	***Thicknes of seams [m.]***	***Depth [m.]***	***Inclination of layer [°]***	***Time [years]***	***Method of mining***	***Location of coal seam [km]***
1	2	3	4	5	6	7
405	1.4-3.0	300	3-10	1898-1916	roof caving	19.5-21.5
406/4	1.8-3.0	340	3-10	1924-25	roof caving	20.0-21.0
408/2	1.5-2.1	440	3-10	1927-52	roof caving	20.2-21.5
409	1.1-1.5	440	3-10	1927-58	roof caving	20.2-21.4
414/1	1.7-2.0	520	3-10	1955-59	roof caving	20.3-21.5
414/2	1.6-1.7	525	3-10	1959-61	roof caving	20.1-21.6
414/3	1.6-1.8	540	3-10	1960-61	roof caving	20.3-21.6
416	1.3-1.4	560	3-10	1964	roof caving	21.1-21.5
417	1.2-2.8	640	3-10	1960-72	roof caving	19.9-21.7
418	1.5-2.1	650	3-10	1927-30	roof caving	20.3-21.3
419	1.6-2.3	660	3-10	1931-37	roof caving	19.8-21.6
501	3.5-4.5	700	3-10	1926-31	roof caving	20.0-21.6
503	2.0-3.2	730	3-10	1928-49	roof caving	20.4-21.5
504	3.5-4.1	740	3-10	1939-51	roof caving	20.4-21.6
507	3.2-3.6	810	3-10	1950-75	roof caving	19.4-21.6
509	2.7-4.2	820	3-10	1962-80	roof caving	19.8-21.5
510	2.5-3.7	800	3-10	1971-83	roof caving	21.2-21.6

Sum : **33.7-47m**

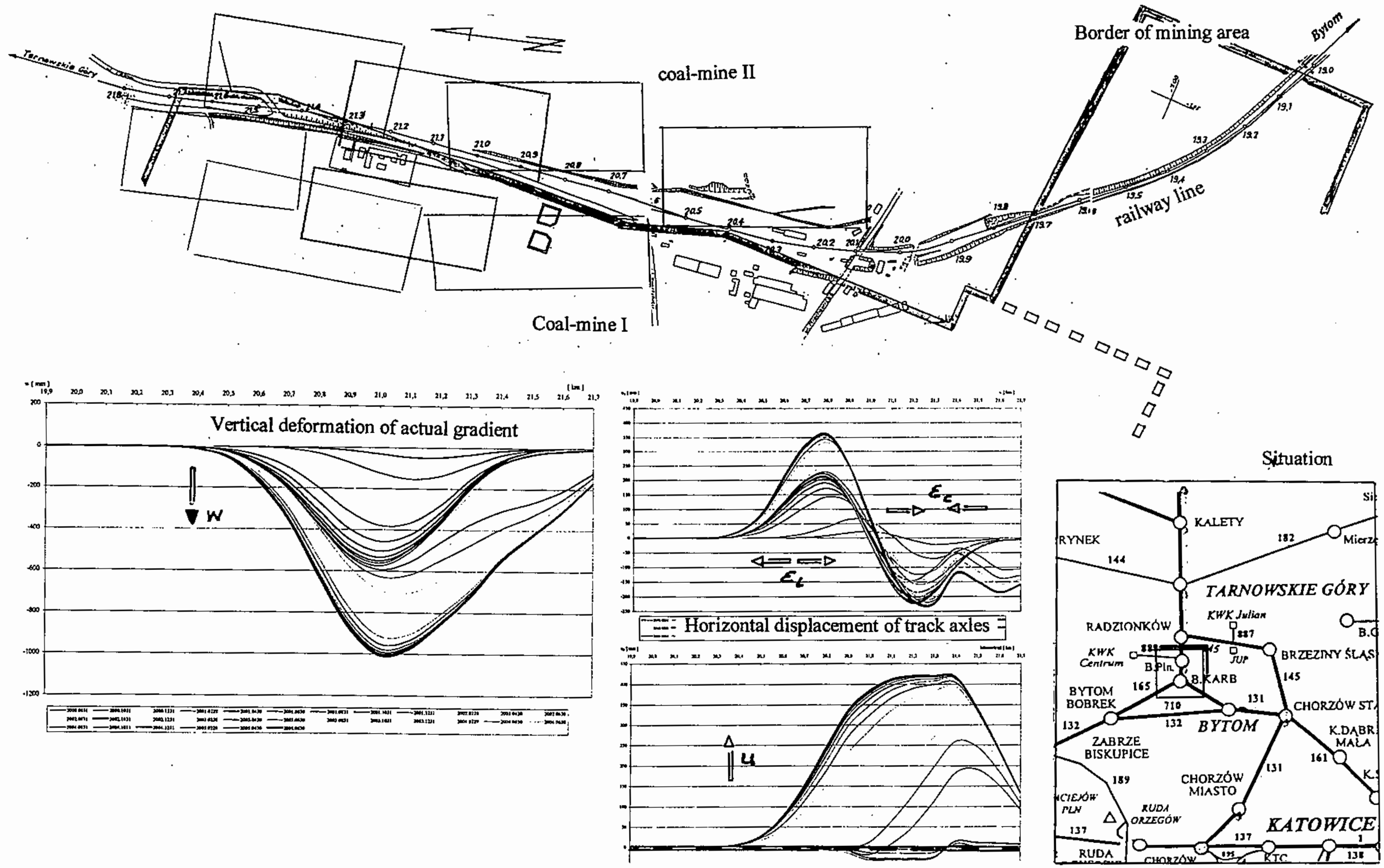

Fig.3 Dynamic character of land surface deformations

Several voids and unfilled chambers remained as an effect of the now discontinued previous ore excavation, at the depth of 60 – 80 m. The pose the hazard of activating discontinuous deformations to the land surface, in the form of caving, faults, crevices. Such deformations are caused by underground (400 – 600 m deep), intense hard coal mining works conducted in the same area, Fig.1a. The discussed mining area holds all natural hazards with various degree of intensity.

Basing on the experience, it has been assumed that the leading hazards are bounces and tremors.

The compilation of the data on tremors occurring in 3 years (1997- 99) proves the existence of serious threats of tremors . The number of tremors recorded in the 3 years reached 5.5 thousand, including 23 tremors of high energy of $E=10^5$J. For the planned mining works, most tremors shall not exceed 2×10^6J, with sporadic occurrence of $E=1 \times 10^7$J tremors. The damages occur at energy $E \geq 10^6$J.

There is an empirical dependence between the energy of surface tremors E and surface vibration acceleration:

$$a = (0.4 - 0.8)\sqrt[3]{E} \quad [\mathrm{mm/s^2}]$$

The maximal accelerations of the vibrations of the subsoil in the discussed area reached $a_{max}=258 \mathrm{mm/sec^2}$. The location of the tremor epicenters in relation to the railway line up to the year of 2002 is presented in Fig.2A.

The coefficient of reinforcing vibration accelerations by overlay in the discussed area varies in the range of 1.1 – 1.7. This coefficient characterizes an increase of acceleration in the loosened overlay in comparison to the vibrations of 'stiff subgrade' in the form of compacted rocks. The close-to-surface Quaternary layers are usually composed of granular soils, where the amplification of accelerations occur. The accelerations in Fig.2A contain the values of the coefficient of reinforcing vibration accelerations of the overlay from Fig.2B.

Forecast and analysis of deformation indices for the subsoil in the zone of the railway protection pillar

The forecast of the continuous deformation indices of the subsoil was prepared in consideration of the mining and geological conditions of the deposits located in the zone of the railway line protection pillar. The protection pillar is this part of the mining area Fig.1a/b , where the extraction works are permitted subject to special limitations and conditions, to protect the surface structures against mining damage On the grounds of the analysis of the forecast results (for years 2000-2006), the following additonal superposition of the deformation components was derived:

- Maximal subsidence in the western zone will exceed $\Delta w=3.0$ m, reaching the value of $w=1.8$ m within the boundaries of the railway line (distance in km: 21.0 – 21.3);
- Maximal subsidence rate will rise to 3-4.5cm /day;
- Maximal land inclination will rise by
- T=9 mm/m, in 21.1- 21.4 km;
- Maximal tensile strains will reach $\varepsilon_t=2.53$mm/m (21.7km) and compression strains will not exceed $\varepsilon_c=3.0$ mm/m.

The above forecast presents increased values of the deformation parameters in comparison with their present value, cumulating their concentration in the zone of the outlined epicenters, especially as far as land subsidence and inclination are concerned.

The components of land inclination, horizontal displacements and unitary strains have a complex spatial distribution. The horizontal displacements in the direction perpendicular to the route axes will be considerably increased, reaching the local values of u=450 mm, which shall compel diagonal overlaps. The increase in horizontal compacting strains will spur the consolidation of the axial forces in the track surface, evoking the necessity of local track distressing. This is particularly important in view of track stability.

Assessment of subgrade strength in the railway protection zone

The railway track, being a linear and relatively fragile structure, is characterized by certain operational and structural sensitivity, especially in view of the mining impact. Although it contains some strength–promoting elements, they are marginally limited to the structural elements of the track structure and the subgrade.

Any plans concerning mining works conducted under such linear structures should first and foremost, include appropriate protection measures.

As already mentioned above, one of the outcome of designed rectification works is increased height of railway embankments. Consequently, such works should be assisted by an increase in the horizontal forces that maintain the stability of the embankments.

The results of test calculations made for the diagrams presented in Fig. 4 show considerable reduction of safety coefficient F, which:

- is estimated in the range of $F^*=1.27\text{-}1.27 < F=1.5$ for the actual geometrical parameters of the existing structures and assumed geo-technical data;
- after considering the possibility of embankment inundation by water, or diagonal flow of water through the body of the embankment, this coefficient is reduced to the value of $F^{**}=1.18 < F$;

- if the para-seismic impact (effect of roof falls) is considered, as well as dynamical impact of vehicles transmitted by the track structure to the subgrade, and increased diagonal inclination of the mining area, the following value of the coefficient may be assumed:
  F*** = 0.99 <F = 1 (state of boundary balance).

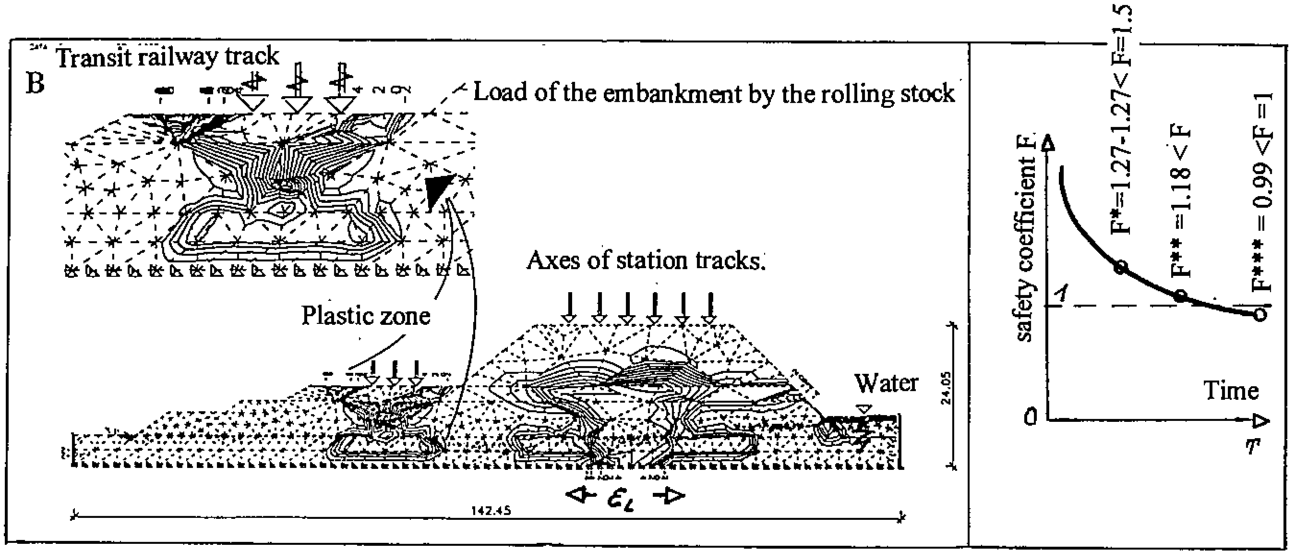

Fig.4 Reduction of safety coefficient F

Due to the stability requirement imposed on the subgrade at the appropriate level of the safety coefficient, the following condition must be fulfilled:

$$F^* = \Sigma P_m / \Sigma P_r \geq F = 1.35\text{-}1.5$$

where:

ΣP_m - sum of the forces maintaining the subgrade in the state of balance;

ΣP_r - sum of the forces reducing the stability of the subgrade.

The upper limit of safety coefficient (F=1.5) is recommended for buttresses of subgrade structures with estimated operational life above 25 years. Thus, the discussed mining impact exerted on the subsoil may pose a hazard of a total loss of load-bearing capacity and stability of transportation earthen structures.

Measurements and assessment of axial stresses in join-tless rail track in mining areas

Pursuant to the technical and safety requirements in force in Europe, it is prohibited to lay out and operate new continuous (joint-less) rail tracks in mining impact areas. The maintenance of the existing continuous rail track operating in mining areas, even for small values of the deformation parameters, calls for special preventive measurement practice, including the following activities:

- land-surveying measurements of deformations;
- measurements of axial forces in rails;
- co-ordination of the above activities with mining protection measures.

Field test schedule and measurement results

The exploitation of the protection pillar (case II) must be preceded by initial measurements of normal stresses in rails. These stresses are mainly evoked by temperature, trains braking, etc.

In typical operation conditions it may be assumed that a rise of temperature by 1K results in an increase of the thermal force [2] by the value of ΔF_t =18 kN/K. For the climactic conditions of the continuous track operation the changes in temperature were assumed in the range of 333 – 243 K (+60/-30° C). To limit the values of thermal stresses in the rails, the range of neutral temperatures was assumed, at which the rails are joined to the railroad tie. If this condition is fulfilled, the biggest thermal forces that may arise in both rails of the continuous (joint-less) track are:

- for compression forces F_t = 1560 kN
- for tensile forces F_t = 2230 kN.

The thermal forces arising in the rails of the continuous track may lead to the loss of its stability combined with buckling of the rail frame. This means a serious failure hazard, due to additional impulses coming from a passing vehicle.

Horizontal strains of the subsoil, especially of a

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[2] For R60- which is a heavy type rail

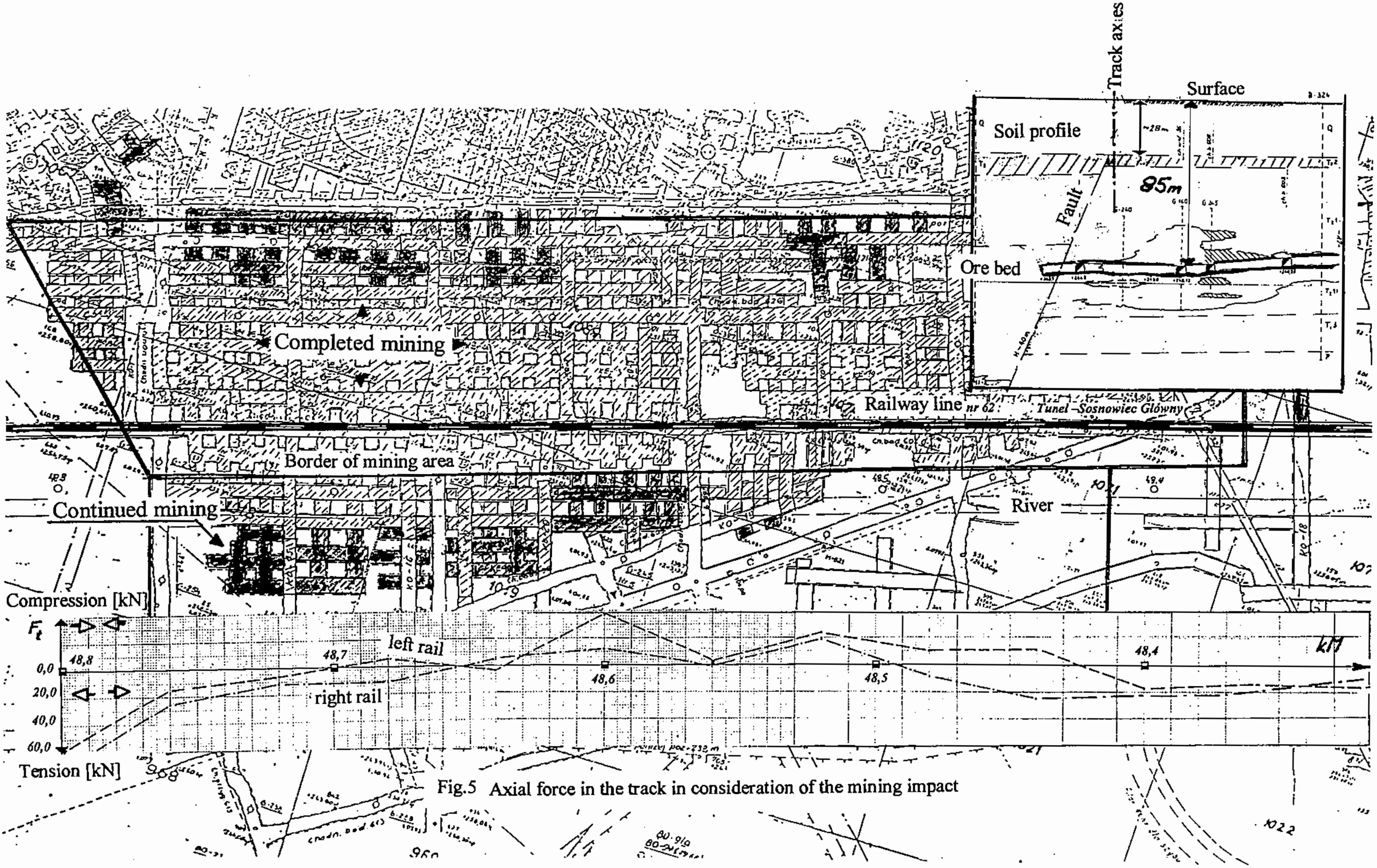

Fig.5 Axial force in the track in consideration of the mining impact

compacting character, because of the friction forces acting on the rail structure, evoke an additional increase in the compression forces in the rails.

The superposition of the thermal forces and dynamic excitations caused by the deformation of the subsoil provoke faster loss of track stability. Thus, checks on actual values of the axial forces in rails are of crucial importance. This task is by no means easy, as the track that is already in operation has some specific state of initial stresses, whereas the mine-induced stresses are an additional factor to be considered.

The methods used for measuring the axial forces in such structures have so far been based on:

- land surveying equipment;
- ultrasound instruments measuring stresses;
- electronic extensometers.

New techniques of stress measurements involve Barkhausen's magnetic noise measurements (Klosek 1999). They are based on the assumption that the intensity of magnetic noises depends on the microstructure of a material and the values of the sums of stresses. The dependence between the intensity of magnetic noises (MP- magnetoelastic parameter or MBN) and values of given stresses may be derived from the calibration curve. The measuring device designed in consideration of the above assumption is characterized by zero state of residual stresses. The measurements have a non-invasive nature are taken under the head of the rail. The readings are recorded on hard disc, which enables full registration of results and their comparative analysis.

The results of exemplary measurements of the axial force in the track in consideration of the mining impact are presented in Fig.5. The measuring device enables credible determination of the variation of the axial forces in the track structure, which facilitates the monitoring of those sections that are particularly threatened by the concentration of the compression strains in mining areas. Thus, appropriate protective measures may be taken.

The mining works on zinc and lead ores are conducted at shallow depth (80 m), by means of chamber and pillar cut and tight sand fill methods, which considerably reduce land surface deformations to 0.15-0.20m. The height of mine chambers reaches 5 –7 m, and their width 2-3 m. The compact layers of dolomite rock deposits secure the safety of the overlay.

Conclusions

The conditions of the two different cases of mining works discussed in the paper lead to the following conclusions:

- The planned roof caving mining activity generates unfavorable concentration of the land deformation parameters – especially in the longitudinal profile of linear engineering structures; this threat may be eliminated by instant rectification works;
- Underground mining activity evokes spatial distribution of the deformation parameters, involving, first and foremost the need to consider horizontal displacements of the route axes;
- The location of the subsidence epicenters in the direct vicinity of transportation systems (embankment foundation base) results in worsened hydro-geological conditions; especially uncontrolled flows of surface waters through the embankment base and extended boundary of interior lakes in troughs with no drainage;
- The need to rectify the gradeline leads to increased height of embankments, which, in turn, compels the urgency to provide better load-bearing capacity and stability of the subgrade operating in complex soil and water conditions, considering the para- seismic and dynamic effects of the rolling stock;
- In some special circumstances the operation of continuous (joint-less) rail track in mine-induced deformation areas may be allowed; but very precise monitoring of the axial stresses in rails is required.

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