Assessment of safe exploitability of undermined objects of the Underground Ore Mining Department of the Mine Management of the PJSC “ArcelorMittal Kryvyi Rih”

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Abstract. The article is devoted to monitoring surface displacement and the condition of monitored objects. The object of research is the process of displacement of the earth’s surface and the state of protected objects of the “United” deposit of the mine department for underground mining of ores of PJSC “ArcelorMittal Kryvyi Rih”. The displacement process is monitored based on long-lasting instrumental observations to determine surface deformations and assess the safety of exploitation of the monitored objects within the mining allotment. The study findings enable ascertaining that in the southern and central parts of the minefield, the displacement process has stopped, but in the northern part, it is still developing, and mining will have no impact on the technological objects of the Mine Management in the next two years. Over the recent two years, actual subsidence rates in the railway area have not exceeded 2.7 mm/month, and they are significantly lower than the permissible values (100 mm/month). The road sections shifting and the base for the removal of the road continue to develop. Mining operations at the deposit “Obiednanyi” have no hazardous impact on the “Schistose Rocks” natural geological reserve, the settlement of Karnavatka and the cemetery “Zakhidne”. Displacement on road and road base sections is in progress. In the vicinity of the settlement of Zhukivka, the maximum relative deformations (3.2 mm/m) are still much lower than the permissible one (6 mm/m), and they will not reach their maximum permissible values in the nearest two three years. In the last year, deformation rates decreased and reached the 2018 figure. Therefore, all the monitored objects within the mining allotment can be safely exploited.

1. Introduction

Ensuring environmental and technical safety in the mining of iron ore by the underground method is secured, among other things, by monitoring the displacement process of the earth’s surface and the state of protected objects within the mining allotment. The monitored objects are adversely affected by surface displacement, resulting in crater formation. The research object is the deposit “Obiednanyi” of the Underground Ore Mining Department of the Mine Management of the PJSC “ArcelorMittal Kryvyi Rih”.

The Underground Mine Management (as an underground mine) of the PJSC “ArcelorMittal Kryvyi Rih” (from now on referred to as the Mine Management) is engaged in mining the rich
iron deposit “Obiednanyi” by ore and country rock caving. Iron ore is extracted in a blind area of the ore deposit within survey axes 159-231 in the 1045m-1065m sublevel.

The dip of the hanging wall rocks varies from 30° in the upper part of the section to 65° in its lower part. Likewise, the dip of the footwall rocks varies from 30° in the upper section to 55° in its lower part.

In the northern part of the ore field (northwards of survey axis 55) from the mark -360 m, a blind area of the deposit occurs. Barren inclusions between it and the main layer reaching 150 m along the strike disappear at a depth of 600 m. In the northwest, this deposit section inclines to the mark - 800 m and joins the deposit “Osnovnyi 95” of the underground mine to form a shared ore body.

The deposit depth “Obiednanyi” increases from -950 m in the south to -1250 m in the north. Heavily watered dolomites occur in the deep hanging wall with karst caverns filled with water. Currently, mining operations are conducted within axes 159-231 in the sublevel 1045-1065 m. Due to deposit thinning, mining operations have been stopped to the south of axis 55.

The displacement process caused by mining operations on the surface has acquired a classic landslide trough with a crater, caving, crack zones and areas of hazardous and general impacts. Currently, the width of the displacement trough across the strike reaches 2.8 km.

The monitored objects on the surface in the footwall of the deposit are:

– The frame bridge PK73 km+200; PK73 km+250;
– The railway track (section 71.74 km) and the access line Kirov station - Shmakove station;
– The railway depot facilities of the PJSC “KZRK”;
– Buildings and facilities of the industrial site of “Pivnichna” mine (the PJSC “Central GZK”);
– Facilities of the Crushing-Sorting Plant (CSP) and the industrial site of the Mine Management;
– Buildings in Kovlska Street;
– The “Schistose Rocks” natural geological reserve of local importance;

The monitored objects on the surface in the hanging wall of the deposit are:

– The settlement of Karnavatka;
– The municipal cemetery “Zakhidne”;
– The section of the motor road “Tekhbaza – Cemetery “Zakhidne”;
– The road base for the motor road section “Tekhbaza – Cemetery “Zakhidne”;
– The settlement of Zhukivka.

The research aims to study the earth’s surface deformations and assess the safety of exploitation of the monitored objects within the mining allotment.

2. Methods
As a result of instrumental measurements in reference points tied to benchmarks of profile lines on the monitored area, the parameters of surface deformations are determined based on analysis, systematization and generalization of the observation data of the current and previous years. According to the results of measurements, graphs of deformations of the earth’s surface are built, which allows you to determine the trend line and predict values for two years in advance.

The measurement results are used for statistical analysis of various mathematical models to forecast deformations’ values for two years ahead.

According to the requirements of the regulatory documents [1–5], mines are to monitor displacement process development. Therefore, since 2016, in the mining allotment of the Mine
Management, the Research Ore Mining Institute of Kryvyi Rih National University has been conducting special observations.

The observations are conducted along profile lines located nearby and on the monitored objects in the displacement area in the hanging wall of the deposit.

There are ten profile lines in the footwall of the deposit: “Railway”, “Axis 159”, “Axis 127”, “Axis 55”, “Depot”, “Axis 11”, “Axis 6”, “Axis 3”, “Axis 220, frame bridge”, “Arch bridge”.

Over the last five years, two sets of instrumental observations (in spring and autumn) have been conducted along profile lines of the footwall.

The research methods are as follows:

- determining elevations and horizontal distances between ground and wall benchmarks;
- levelling wall benchmarks on buildings of the industrial site, the railway depot of the PJSC “KZRK”, the frame and the arch bridges;
- levelling rail joints on the section 71km - 74 km of the railway track;
- measuring chords and butt gaps on the section 71km - 74 km of the railway track;
- laying connecting passages between profile lines - geometric levelling of IV class;
- office analysis of observation results.

There are nine profile lines in the hanging wall: “Settlement of Zhukivka”, “Road”, “Cemetery”, “Sklonenie”, “Axis 105”, “Axis 25”, “Axis 6”, “Axis 54”, “Road base”.

The following observations are conducted at the observation station of the hanging wall of the deposit “Obiednanyi”:

- along the profile lines “Axis 54”, “Axis 6”, “Axis 25”, “Cemetery” – one set;
- along the profile lines “Road Basis” “Road” - two sets (in spring and autumn)
- along the profile lines “Axis 105”, “Sklonenie”, and “Settlement of Zhukivka” - four sets of observations.

The work includes the following stages:

- determining elevations and horizontal distances between ground and wall benchmarks;
- laying connecting passages between profile lines - geometric levelling of IV class;
- office analysis of observation results.

After office analysis, the observation results are summarized in the sheet of vertical displacements (subsidence), vertical displacement rates, vertical deformations of intervals between benchmarks, horizontal deformations of intervals between benchmarks, horizontal displacements of benchmarks.

3. Results and discussion

3.1. Study of the displacement process in the footwall of the deposit “Obiednanyi”

According to the nature of the displacement process development in the footwall of the deposit “Obiednanyi”, the mine field can be conditionally divided into three sections: I section - southern (southwards of axis 80), II - central (axes 80-55) and III - northern (northwards of axis 55).

In the southern section of the mine field, measurements were made along the profile lines “Arch bridge” and “Axis 220”. Mining operations in this section were suspended in 1990. At present time, the vertical and relative horizontal deformations rates are within the measurement accuracy.

Observations of the behaviour of the arch bridge abutments above the former channel of the Saksagan River (profile line “Arch Bridge”) show that over 29 years, total subsidence of wall benchmarks has made 9mm to 32mm, i.e. the average annual rate of subsidence makes 0.3-1.1 mm/year (0.03-0.09 mm/month). However, last year subsidence does not exceed 1 mm/year.
On the profile line “Axis 220” benchmarks, total subsidence for the 56-year observation period ranges from 33 mm to 399 mm, and the average annual subsidence rate is 0.6-7.1 mm/year. Last year subsidence rates do not exceed 5 mm/year.

In the central section of the mine field (survey axis 80 - survey axis 55), mining operations were finished in 1997 due to deposit thinning. Instrumental observations are conducted along the profile lines “Axis 3”, “Axis 6”, “Axis 11”, and “Depot”.

Total subsidence by ground benchmarks of the profile line “Axis 3” for the 58-year observation period ranges from 9 mm to 480 mm. These benchmarks’ average annual subsidence rate is 0.2 - 8.3 mm/year.

Total subsidence by ground and wall benchmarks of the profile line “Axis 6” for the 56 years of observations ranges from 376 mm to 537 mm, i.e. 6.7 - 9.6 mm/year.

Average monthly subsidence rates for the last three-year period along the “Axis 3” and “Axis 6” profile lines do not exceed 1 mm/month.

Total subsidence by benchmarks of the profile line “Axis 11” for the 44 years of observations ranges from 272 mm to 557 mm, i.e. 6.2 - 12.7 mm/year.

Average monthly subsidence rates for the last three-year period do not exceed 1.5 mm/month.

Total subsidence by the profile line “Depot” benchmarks for the 28 years of observations ranges from 228 mm to 273 mm, i.e., 8.1-9.8 mm/year. Last year subsidence rate is 0.25-0.33 mm/month.

As is seen in figure 1, annual subsidence along all the profile lines of the southern and central parts of the footwall for the last year does not exceed 10 mm.

![Figure 1. Annual subsidence along the profile lines of the footwall (southern and central parts) in 2021.](image)

It can be concluded that, according to paragraph 2.22. of [1], the displacement process in the southern and central parts of the footwall is finished.

In the northern section of the footwall of the mine field (survey axis 55 - survey axis 263), instrumental observations are conducted along the profile lines “Axis 55”, “Axis 127”, and “Axis 159”.

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Figure 1. Annual subsidence along the profile lines of the footwall (southern and central parts) in 2021.
Vertical subsidence along these profile lines increases towards the hanging wall. Depending on a year of observation, the maximum subsidence is approximated by linear dependences with a sufficiently high degree of approximation reliability ($R^2$ value):

- along the profile line “Axis 55” $y = 23.9 \cdot x + 534.3$, approximation reliability ($R^2$ value) is 0.9976;
- along the profile line “Axis 127” $y = 52.2 \cdot x + 393.5$, approximation reliability ($R^2$ value) is 0.9272;
- along the profile line “Axis 159” $y = 23.9 \cdot x + 534.3$, approximation reliability ($R^2$ value) is 0.9298.

Forecast values of subsidence rates in the northern section of the footwall for 2022-2023 make 13.5 mm/year (1.1 mm/month) to 52.2 mm/year (4.4 mm/month) over the entire displacement area.

Annual subsidence along all profile lines of the northern part of the footwall for the last year exceeds 10 mm (figure 2).

![Annual subsidence along profile lines](image)

**Figure 2.** Annual subsidence along the profile lines of the footwall (northern part) in 2021.

It can be concluded that, according to paragraph 2.22 of [1], the process of displacement in the northern section of the footwall is still developing.

Also, in the footwall, observations are made along the profile line “Railway”, which crosses the southern, central, and northern footwall.

Subsidence along the “Railway” profile line increases from south to north in the section PK73800 - PK71800 and decreases from south to north in the PK71800 - PK 71250.

Average monthly subsidence rates by benchmarks of the profile line “Railway” for the last two-year period do not exceed 2.7 mm/month, clearly seen in figure 3.
3.2. Study of the displacement process in the hanging wall of the deposit “Obiednany”

The trough of the hanging wall rock displacement can be conditionally divided into three sections considering the mine field from south to north: southern, central and northern.

In the southern section of the hanging wall, mining finished in 1990. Observations are conducted along the profile line “Axis 54”. In 2021, surface subsidence ranged from 1 mm to 7 mm. Total subsidence of the last three-year period does not exceed 15 mm.

In the central section of the hanging wall (survey axis 80 - survey axis 55), mining operations stopped in 1997. Observations are conducted along the profile lines “Axis 6” and “Axis 25”.

In 2021, surface subsidence along the “Axis 6” profile line made 2 mm to 7 mm. Total subsidence of the last three-year period does not exceed 26 mm.

Along the profile line “Axis 25”, the largest subsidence for the last three-year period was recorded in 2020 (from 29 mm to 40 mm). However, over the last year, subsidence has significantly reduced in size. In general, over the last three years, the total subsidence along the profile line “axis 25” has not exceeded 50 mm.

Graphs (figure 4) shows annual subsidence along the profile lines of the southern and central sections of the hanging wall in 2021.

According to paragraph 2.22 of [1], the displacement process is considered finished for the hanging wall if surface subsidence during a year does not exceed 50 mm. In 2021 subsidence, the southern and central sections were well below 50 mm/year (figure 4).

Thus, it can be concluded that the displacement process is finished in the southern and central parts of the hanging wall.

In the northern section (northwards of axis 55.), observations were made along six profile lines of ground benchmarks: “Axis 105”, “Sklonenie”, “Cemetery”, “Road”, “Road base” and “Settlement of Zhukivka”.

Analysis of the observation data in this section reveals that displacement continues to develop, its activity in different trough sections varies. The decrease in displacement activity is caused

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**Figure 3.** Average monthly subsidence rates by benchmarks along the profile line “Railway” in 2020-2021.
Figure 4. Annual subsidence along the profile lines of the footwall (southern and central part) in 2021.

by the development of the northern blind area of the deposit.

Subsidence by benchmarks on the profile line “Axis105” is growing every year towards the crater formed in 1985, and it equals 71 - 16900 mm (as of 07 November 2021). Surface subsidence tends to grow gradually every year. Depending on a year of observation, the maximum subsidence is approximated by the relationship \( y = 67.717 \cdot x + 16251 \), approximation reliability (\( R^2 \) value) is 0.9592. Over the last year (15 November 2020 - 07 November 2021), surface subsidence on the profile line “Axis105” was recorded 14 mm (Rp58) to 72 mm/year (Rp18), i.e. 1.2 - 6.0 mm/month. It should be noted that while in 2020, annual subsidence by the benchmarks of the profile line “Axis 105” increased by a factor of 1.5 - 2 on average as compared to 2019, in 2021, annual subsidence decreased by almost all benchmarks as compared to 2020 and almost reached the figures of 2019. This is demonstrated in figure 5.

The profile line “Axis105” crosses the crater formed in 1985. Directly around the crater, a caving zone was formed with terraces of over two meters and cracks of dozens of centimetres. In 2012, the crater turned out again, and another crater of 76 m in diameter was formed in the west within axes 151-159. Total subsidence over the 37 years (1984-2021) along the profile line “Sklonenie” ranges from 970 mm (Rp35) to 7706 mm (Rp12). Depending on a year of observation, the maximum subsidence is approximated by the relationship \( y = 107.8 \cdot x + 7175.8 \), the approximation reliability (\( R^2 \) value) is 0.989. Over the last year, surface subsidence by the benchmarks of the profile line “Sklonenie” has decreased compared to that in 2019-2020 (figure 6).

In 2021, annual subsidence on the profile line “Cemetery” also decreased compared to 2019-2020 (figure 7).

Currently, the main part of the cemetery area falls into the displacement trough, and the southern part (axes 103–159) - into the displacement area. The boundary of the crack zone goes at a distance of 50 m in the south and 190 m in the north from the cemetery area. No visible cracks are found in the cemetery area.

Along the profile line “Road”, the subsidence of the last year period is 9 - 88 mm/year
Figure 5. Annual subsidence by the profile line “Axis 105” benchmarks in 2019-2021.

Figure 6. Annual subsidence by benchmarks along with the “Sklonenie” profile in 2019-2021.

(0.8-7.3 mm/month). Annual subsidence along this profile line and all the other profile lines of the northern part of the hanging wall tend to decrease. Thus, in 2021 annual subsidence of the surface decreased by all the benchmarks (except for one benchmark) of the profile line as compared to 2020 (figure 8).

The profile line “Road base” is located within axes 15-87 and LSP+450 - LSP+1350 above the depleted area of the deposit in the “old” zone of terraces and the zone of craters. Along this line, annual subsidence in 2021 by a significant number of benchmarks exceeds 50 mm/year, but it also tends to decrease compared to 2020 (figure 9).
Along the profile line “Settlement of Zhukivka”, the last year subsidence rates in the residential area make 9 - 25 mm/year (0.8 – 2.1 mm/month). In 2021, the residential area annual subsidence decreased slightly by each benchmark of the profile line “Settlement of Zhukivka” compared to 2019 - 2020 and almost reached the figures of 2018 (figure 10).

For the conditions of residential buildings of Zhukivka, according to the methodology presented in [6] (Section 4), the permissible deformation values were calculated. Deformations of the earth’s surface are considered permissible if they can damage the facilities to the extent that the facilities require normal maintenance and repair works and can be exploited by their intended purpose. According to the calculations, permissible horizontal deformations for buildings of Zhukivka equal $|\varepsilon|_p = 6.0 \cdot 10^{-3}$. Comparison of the calculated values of permissible
Figure 9. Annual subsidence along the “Road base” profile line in 2019-2021.

Figure 10. Annual subsidence along the profile line “Settlement of Zhukivka” in 2018-2021.

relative horizontal deformations for buildings of Zhukivka $|\varepsilon_p| = 6.0 \cdot 10^{-3}$ with actual maximum relative horizontal deformations along the profile line “Settlement of Zhukivka” in 2021 $|\varepsilon|_{\text{max}} = 3.2 \cdot 10^{-3}$ enables the conclusion that the latter is two times less than the permissible ones. On figure 11 plots the maximum relative horizontal deformations along the profile line “Settlement of Zhukivka” with a forecast for two years.
Figure 11. Maximum relative horizontal deformations along the profile line “Settlement of Zhukivka” in 2012-2021 with a forecast for two years.

Analysis of the graph in figure 11 enables the conclusion that in 2022 the forecast values of the maximum relative horizontal deformations along the profile line “Settlement of Zhukivka” will reach 3.5 mm/m and 3.7 mm/m - in 2023. These will not exceed values of permissible relative horizontal deformations for buildings of the settlement $\varepsilon_p = 6.0 \cdot 10^{-3}$ either.

4. Conclusions

The frame bridge is 73km+200m-250m of Ukrzaliznytsia is located within survey axes 112.122 in the southern section of the mine field, where mining operations were ceased in 1990, and the displacement process finished. Over the entire observation period, the average annual rates of wall benchmarks subsidence have not exceeded 7.1 mm/year. Subsidence rates of the last year (06 September 2020 - 25 September 2021) are less than 5 mm/year (0.5 mm/month). Therefore, mining operations do not and will not have adverse impacts on the earth’s surface in the area of the frame bridge.

The Piatykhatky - Kryvyi Rih line of Ukrzaliznytsia (PK71 - PK74km) and the Kirov station’s connecting (access) line - Shmakove station are in the trough and the footwall rocks displacement zone. These sections of the railway track are located at a distance of 200 - 300 m from the deposit in crop and over 300 m from the zone of possible crater formation. Since 1981, the railway tracks have passed through the displacement zone (in the 1980s and 1990s within axes 104-135). At present, the actual boundary of the crack zone passes near the railway track within axes 87-135. The displacement zone crosses the railway tracks within axes 63-143. According to paragraph 4.8 of [1], main and access tracks can be located in the displacement and crack zones with a subsidence rate of no more than 100 mm/month. The actual annual rates of surface subsidence in the area of the Ukrzaliznytsia track and the access track have not exceeded 2.7 mm/month over the last two years, which is significantly lower than the permissible values (100 mm/month). Analysis of the field observations shows that the displacement process in the deposit’s footwall has no adverse impact on the railway track of Ukrzaliznytsya and the access track. Therefore, there is no need for special protection measures for these facilities.

The railway depot of the PJSC KZRK was affected by surface subsidence during mining
operations in the central section of the mine field (up to 1997). Analysis of the instrumental observations data along the profile lines “Axis 11” (ground benchmarks) and “Depot” (wall benchmarks on the depot and warehouse buildings) shows that the last year maximum annual rates of subsidence are from 9 mm (Rp6 profile line “Axis11”) to 13 mm (Rp38 on the warehouse building on the profile line “Depot”). Current underground mining operations to the north of survey axis 55 do not affect the depot facilities.

The shaft and the machine room of the mine “Pivnichna” (the PJSC Central GZK) fall into the zone of displacement caused by current mining operations. The maximum average annual subsidence rates are 7-15 mm/year (0.6-1.2 mm/month). The average annual increase in relative horizontal tensile strains is $\Delta \epsilon = + (0.1 - 0.2) \cdot 10^{-3}$. Total subsidence $\eta = (272 - 485)$ mm.

In 2021 - 2022, rates of subsidence and horizontal deformations will remain at the current level and have no adverse impact on the “Pivnichna” mine facilities.

The Crushing-Sorting Plant is located on the industrial site of the Mine Management within survey axes 96 - 44, LSP +0.0m and includes some facilities. The CSP area falls into the southern and central (south) sections of the mine field, where the boundaries of the displacement zones have remained unchanged since 1991. Development of the blind area of the deposit (northwards of axis 55) will have no adverse impact on the facilities of the CSP complex. The subsidence rates of the wall benchmarks on the Mine Management industrial site buildings are within the measurement accuracy. Current mining operations have no impact on the industrial site.

The condition of buildings in Kovalska Street has been unchanged for the recent 15 years. Therefore, in this area, the displacement process has finished.

The “Schistose Rocks” geological natural reserve of local importance is located on the right bank of the river Saksagan within axes 79 - 103 and does not fall into the displacement zone. In addition, according to [1] (paragraph 4.19), “The arable lands, urban forest parks, forest plantations, and similar natural objects that fall into the earth’s surface displacement zone may be used for their intended purpose, except for areas in a crater, sinkhole and terrace zones”. Therefore, the “Schistose Rocks” natural geological reserve of local importance can be safely exploited.

In 2022 - 2023, one should not expect the displacement zone boundaries to move; the crack zone boundary within axes 159-223 will move 50-80 m westwards of the current crack zone boundary; current mining operations at the deposit “Obiednanyi” will have no adverse impact on the area and residential buildings of the settlement of Karnavatka.

The municipal cemetery “Zakhidne” area is located within axes 103 - 207, LSP+2200m. LSP+2800 m. It started in 1993. According to paragraph 4.2. of [1], the cemetery belongs to the III category of protected objects, for which the earth’s surface deformations can result in underflooding and groundwater contamination. In 2022 - 2023, the crack zone boundary within axes 159-223 will move 50-80 m westwards of the current crack zone boundary, but it will not reach the cemetery boundary. Mining of the deposit up to the 1065 m level will have no impact on the area of the cemetery “Zakhidne”.

According to paragraph 4.2 of [1], the motor road belongs to the III category of protected objects, on which deformations of the earth’s surface in the crack zone have hazardous impacts. According to paragraph 4.8. of [1], motor roads are permitted in the displacement and crack zones with a subsidence rate of no more than 100 mm/month. Analysis of the observation data along the profile line “Road” demonstrates that the landslide process has resulted in a smooth deflection of the surface without cracks and loss of integrity. The main type of horizontal deformation is compression. As the analysis of observations shows, compressional deformations are often precursors of craters, sinkholes, or a zone of severe deformations. Further mining of the reserves on the northern flank of the mine field will lead to the activation of a landslide process in the motor road area.

According to [7], a crater should be expected after complete mining of level 1045 m of the
deposit “Obiednanyi” by the Mine Management and level 1240 m by “Rodina” underground mine within axes 223-295, LSP+850 - LSP+1350 (justification by the Mine Management). Mine Management is currently mining iron ore in the blind area within axes 150-239 in the sub-level 1045-1065 m. “Rodina” mine performs mining operations on a level of 1390 m northwards of axis 152. The forecast for a crater formation at deepening and mining along the strike remains valid. In 2014, a section of the road with a possible crater was blocked off near Rp12 - 43; the traffic was stopped, thereby taking appropriate protective measures.

The profile line “Road base” is located above the depleted section of the deposit in the “old” terrace zone and the crater zone and falls into the displacement zone and the crack zone caused by underground mining. The displacement process on the profile line “Road base” section is still developing. According to paragraph 1.6 of [1] and paragraph 4 of [8], construction facilities are not allowed on the surface above depleted mineral deposits until the end of the displacement process.

The settlement of Zhukivka falls into the mining allotment of the Mine Management (axes 267-307, LSP+1700m - LSP +1950m) and the mining allotment of “Rodina” mine (axes 180-200, LSP +1750m - LSP +2000m). Thus, it is located at the joint of mining operations of the Mine Management and “Rodina” mine on the hanging wall of the depleted shared deposit and falls in the displacement zone caused by operations of these mines. Therefore, paragraph 4.2 of [1] states that the settlement belongs to the III category of protected objects. At present, mining of the deposit up to level 1065 m does not cause surface deformations above the permissible values for residential facilities of the settlement. Therefore, the measures to protect the settlement involve maintenance until the actual relative horizontal deformations do not exceed the calculated permissible value for residential buildings \[ \varepsilon_p = 6.0 \cdot 10^{-3} \].

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