Study of permissible dynamic load on high-pressure gas pipe laying site in connection with blasting operations during open-pit mining

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Abstract. The paper presents the results of a study of permissible dynamic load on high-pressure gas pipe laying site of the II category located within the mining lease boundaries, in connection with carrying out blasting operations at the open-pit mine of JSC Sukholozhsktsement. The procedure of IM UrB RAS for calculating the permissible distances from the technological explosion in the mine to the protected object (gas pipeline) depending on the explosive weight in the stage, coefficient of soil conditions and permissible velocity of seismic vibrations is presented. It is found that depending on the explosion depth in the mine and using corresponding geological data, by changing the weight in the delay stage, it is possible to completely eliminate the negative effect of explosion on pipe laying area. A calculation scheme is also proposed to determine the safe distances to high-pressure gas pipeline depending on the angle of open pit side and blasting depth.

1. Introduction
The problem of the study is that a high-pressure gas pipeline (0.3 to 0.6 MPa) of the II category is located near the mining lease of JSC Sukholozhsktsement. It is required to provide seismic safety of gas pipeline operation and determine the permissible approach distances for blasting and mining operations in general, as well as permissible seismic resistance of the location site.

The work is aimed at increasing the level of safe operation of the gas pipeline and establishing restrictions on the impact of mining operations in the direction of the place of gas pipe laying.

Within the framework of the study, it was necessary to solve two problems:
– to determine the permissible velocities of seismic vibrations and soil displacements in the area of high-pressure gas pipe laying of the II category with a diameter of 225 mm, at which safe operation is maintained;
– determine the safe distance (zone, slope value) from the gas pipeline, in which seismic intensity above 6 and 7 is prohibited due to geological features.

Administratively, the gas pipeline route runs from the southern boundary of the town of Sukhoy Log, along the Sukhoy Log-Kamyshlov highway, to the settlement of Kuryi.

Geomorphologically, the gas pipeline is located on a steeply-sloping plateau-like plain of the eastern slope of the Middle Urals, 0.5–3.6 km from the river Pyshma. The slopes of the river valley are complicated by erosional-karstic ravines. The natural relief of the route is relatively smooth with a slope to the north-east towards the river Pyshma. Absolute relief elevations vary within 145–166 m. The difference in existing land elevation points in this area is 21 m.
The pipeline section is located in the development zone of fine-grained, massive, gray, brown-gray, rarely dark brecciated limestones.

The territory of the town of Sukhoi Log and adjacent territories belong to the area with seismic intensity 6 according to MSK-64 scale. The soils are classified as categories I and II in terms of seismic properties.

2. Procedure for studying the velocity of seismic vibrations

The dynamics of effect from blasting operations is manifested in seismic vibrations of the ground. The permissible seismic effect in large-scale blasting is determined in two directions. Firstly, the effect of seismic vibrations from blasting operations should not lead to rock mass instability within the site boundaries. Secondly, ground vibrations under the structure (high pressure gas pipeline) should not lead to its destruction. The developments of IM UrB RAS are used to calculate seismic stability of soils at the sites and determine the permissible values of vibration velocity for a high-pressure gas pipeline within the mining lease of the open-pit mine of JSC Sukholozhtsement [1 - 6].

The permissible value of seismic vibration velocity is in accordance with permissible stress value in the rock mass. The permissible stress value characterizes seismic resistance of a mine working (see expression (1)):

\[
\left[\sigma_{st}\right] + \left[\sigma_{dyn}\right] \leq \sigma_{per},
\]

where \(\sigma_{st}\) is the static stress in the rock mass surrounding the mine working, MPa; \(\sigma_{dyn}\) is the dynamic stress in the rock mass (in the neighborhood of a mine working), MPa; \(\sigma_{per}\) is the permissible stress value, MPa.

All subsequent calculations imply that the condition of expression (1) is met and the rock mass under study is stable. In approximation, static tensile rock strength \(\sigma_{tens}\) increased by 10-30% can be assumed as permissible stress value \(\sigma_{per}\) [5]. It should be noted that \(\sigma_{tens}\) determined in a sample differs considerably from the value determined in the rock mass due to macroadisturbances. In the rock mass, \(\sigma_{tens}\) is 5-10 and more times lower than in sample [3], because rocks, as a rule, are intermixed; this value is also significantly influenced by fracturing and filling material. The rock mass tensile strength is determined using the coefficient of structural weakening. However, due to the scale effect, this coefficient can be currently determined only experimentally, whereas it can differ significantly in different parts of the rock mass in one rock. Considering that the methods for determining the real state of the rock mass are still in development and require additional research, for approximate calculations the strength of rocks in a hard rock mass can be taken as \(0.1\sigma_{tens}\) of the value in the sample.

According to [3], the permissible rate of rock mass displacement can be determined by the expression:

\[
\nu_{per} = \frac{2\sigma_{per}}{\gamma C} \cdot 981 \cdot 10^3 \text{ cm/s},
\]

where \(\sigma_{per}\) is the permissible stress value, kgs/cm\(^2\); \(\gamma\) is the rock density, t/m\(^3\); \(C\) is the sound speed in rock, cm/s.

Adhering to the values of indicators, according to the SI system, expression (2) can be written in the following form:

\[
\nu_{per} = \frac{\sigma_{per}}{\gamma C} \cdot 2604.1 \text{ m/s},
\]

where \(\sigma_{per}\) is the permissible stress value, MPa; \(\gamma\) is the rock density, t/m\(^3\); \(C\) is the sound speed in rock, m/s.
The velocity of seismic vibrations depending on the explosive weight in the stage and distance from the explosion to the protected object can be determined according to [3] by the following expression (at a distance less than 1500 m).

\[ v = K \sqrt{\frac{Q}{R}} \text{ cm/s}, \]  

(4)

where \( v \) is seismic vibration velocity, cm/s; \( Q \) is the weight of simultaneously blasted charges (weight of explosives in the delay stage), kg; \( R \) is the distance to the object, m; \( K \) is the coefficient depending on soil conditions (rocky, semi-rocky (\( K = 200–300 \)); sandy clay (\( K = 300–450 \)); loose, watered and fill-up ground (\( K = 450–600 \)).

Thus, having determined the permissible vibration velocity of open pit side section (expression (3)) and substituting the obtained value into expression (4), we can determine, depending on the distance, permissible explosive weight per delay stage. Considering the fact that blasting supplies can currently provide an independent operation of each explosive charge in the blasthole, then using such calculations, it is possible to optimize the parameters of drilling and blasting operations and achieve a significant reduction in the seismic effect of explosion on protected rock mass and object.

The presented method for solving the problem allows making preliminary calculations, estimating the possible effect of blasting operations on the protected object (high pressure gas pipeline) and taking appropriate engineering decisions for mining operations.

In practice, the research procedure includes full-scale measurements of magnitudes of seismic waves during blasting in open-pit mines, statistical processing of experimental data, monitoring of the influence of blasting operations on protected objects and calculations of permissible values of explosive charges in various conditions.

After measurements, the obtained values (vector value of maximum resultant velocity of ground vibrations) are compared with design permissible values of seismic vibration velocity.

Thus, a comparison of design and experimental data makes it possible to observe seismic resistance of the rock mass during blasting near the protected object. Special experimental studies are not provided in this paper, only calculations from the research design are presented.

### Table 1. Initial data and design values of seismic resistance of soils

| Rock                        | Density, \( \text{t/m}^3 \) | Compressive strength in a sample, MPa | Tensile strength in a sample, MPa | Poisson’s ratio | Elastic modulus, GPa | Longitudinal wave velocity in ground, m/s | Transverse wave velocity in ground, m/s | Accepted coefficient of structural weakening | Accepted permissible stress value, MPa | Accepted permissible velocity of ground vibrations, m/s |
|-----------------------------|-----------------------------|-------------------------------------|----------------------------------|----------------|----------------------|------------------------------------------|------------------------------------------|-------------------------------------------|--------------------------------------|------------------------------------------|
| Fill-up ground              | 1.72                        | 0.18                                | 0.02                             | 0.25           | 0.001                | 1300                                     | 751                                       | 1.00                                      | 0.18                                  | 0.02                                     |
| (breakstone with impurities)| 1.86                        | 0.22                                | 0.03                             | 0.25           | 0.001                | 1350                                     | 779                                       | 1.00                                      | 0.22                                  | 0.03                                     |
| Hard continental loam       | 2.00                        | 0.25                                | 0.03                             | 0.25           | 0.001                | 1400                                     | 808                                       | 1.00                                      | 0.25                                  | 0.03                                     |
| (strongly swollen)          | 1.82                        | 1.50                                | 0.15                             | 0.35           | 0.025                | 1700                                     | 817                                       | 0.80                                      | 1.20                                  | 0.12                                     |
| Hard deluvial loam          | 1.89                        | 2.00                                | 0.20                             | 0.35           | 0.025                | 1930                                     | 927                                       | 0.80                                      | 1.60                                  | 0.16                                     |
| Hard alluvial sandy loam    | 1.96                        | 2.50                                | 0.25                             | 0.35           | 0.025                | 2160                                     | 1038                                      | 0.80                                      | 2.00                                  | 0.20                                     |
| (non-swelling soil)         | 1.72                        | 1.00                                | 0.10                             | 0.33           | 0.017                | 1500                                     | 756                                       | 0.70                                      | 0.70                                  | 0.07                                     |
| Hard rocks (limestone)      | 1.81                        | 1.50                                | 0.15                             | 0.33           | 0.017                | 1700                                     | 856                                       | 0.70                                      | 1.05                                  | 0.11                                     |
| Hard alluvial sandy loam    | 1.89                        | 2.00                                | 0.20                             | 0.33           | 0.017                | 1900                                     | 957                                       | 0.70                                      | 1.40                                  | 0.14                                     |
| (non-swelling soil)         | 1.84                        | 2.50                                | 0.31                             | 0.29           | 0.028                | 1450                                     | 789                                       | 0.50                                      | 1.25                                  | 0.16                                     |
| Hard alluvial sandy loam    | 1.92                        | 2.65                                | 0.33                             | 0.29           | 0.028                | 1575                                     | 857                                       | 0.50                                      | 1.33                                  | 0.17                                     |
| (non-swelling soil)         | 2.00                        | 2.80                                | 0.35                             | 0.29           | 0.028                | 1700                                     | 925                                       | 0.50                                      | 1.40                                  | 0.18                                     |
| Hard alluvial sandy loam    | 2.42                        | 64.30                               | 8.00                             | 0.26           | 38.00                | 4590                                     | 2614                                      | 0.10                                      | 8.00                                  | 0.80                                     |
| (non-swelling soil)         | 2.70                        | 95.60                               | 9.56                             | 0.26           | 42.00                | 5750                                     | 3275                                      | 0.10                                      | 9.56                                  | 0.96                                     |
3. Calculation of ground seismic resistance during technological explosions

The necessary initial data for calculating seismic resistance in the available geological materials are not presented in full. Therefore, part of the data for the calculation was taken from the reference literature [7–13].

Initial data and design values of seismic resistance of soils are presented in Table 1.

Based on the initial data, a calculation and a comparison between design vibration velocity and permissible vibration velocity, which for seismic intensity of 6–7 is $v_{per} = 0.06$ m/s, were made [13]. In terms of seismic resistance, design permissible velocities (gray boxes in Table 1) exceed the mentioned value in most cases, which indicates a significant reserve of seismic resistance in loam and rocky ground. Fill-up ground can lose its seismic resistance at vibrations of 0.03 m/s. Considering the diagram of gas pipe laying in the mentioned soils, for further calculations of dangerous explosive weight in the delay stage causing seismic intensity above 7 near the gas pipeline, the value of permissible velocity $v_{per} = 0.06$ m/s.

The shortest distance from the open-pit mine to gas pipeline is characterized by the following points. Points (1-К and 2-К) at the boundary of open-pit mine of JSC Sukholozhktsement and points (1-Г and 2-Г) on the protected object are selected (Figure 1).

Figure 1. Points (1-К and 2-К) at the boundary of open-pit mine of Sukholozhktsement and points (1-Г and 2-Г) on the protected object (high-pressure gas pipeline).

According to the selected points and permissible velocity of ground vibration $v_{per} = 0.06$ m/s at the following coefficients of soil conditions: 300 (rocky, semi-rocky); 450 (sandy clay); 600 (loose, watered and fill-up ground) the calculations presented in Table 2 were made.

| Object                | Point number | Shortest distance from open pit boundary to protected object, $L$, m | Permissible vibration velocity of undeveloped soil, $v_{per}$, m/s | Average coefficient of soil conditions, $K$ | Dangerous explosive weight per delay stage for slope and ground structures, $Q$, kg |
|-----------------------|--------------|---------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------|----------------------------------------------------------------------------------|
| High-pressure gas pipeline of II category, 225 mm in diameter | 1 – Г       | 1 – К                                                              | 930                                                                  | 0.06                                        | 300  142996.80                      |
|                       | 2 – Г       | 2 – К                                                              | 625                                                                  | 300  80435.70                              | 450  97656.25                             |

Table 2. Design values of dangerous explosive weight per delay stage
4. Determination of safe distances for high-pressure gas pipeline

To determine the permissible distances to the protected object, by transforming formula (4), \( R(L_0) \) was expressed and the following expression was obtained:

\[
R(L_0) = \frac{Q K^2}{g^2} \text{ m.} \tag{5}
\]

Using the obtained formula, a multivariate calculation of permissible distances from the explosion to the protected object was made for 5 engineering-geological elements, depending on the explosive weight in the stage, coefficient of soil conditions and permissible velocity of seismic vibrations. Depending on the depth of explosion in the open-pit mine and corresponding geological data, it is possible to completely eliminate the negative explosive effect on gas pipe laying area by changing the weight in a delay stage.

To determine safe distances to high-pressure gas pipeline depending on the angle of open pit side and the depth of blasting, the following expression is proposed:

\[
L_{\text{H}(x)} = L_0 + \sqrt{\left( \frac{H_{\text{bl}(x)}}{\sin(\alpha)} \right)^2 - H_{\text{bl}(x)}^2} \text{ m,} \tag{6}
\]

where \( L_{\text{H}(x)} \) is safe distance to the protected object at depth \( H_{\text{bl}(x)} \); \( L_0 \) is permissible distance from the open-pit boundary to high-pressure gas pipeline; \( H_{\text{bl}(x)} \) is the depth of blasting; \( \alpha \) is the angle of open pit side.

Let us consider an example with the following parameters: explosive weight \( Q = 260 \text{ kg} \); permissible distance \( L_0 = 86 \text{ m} \) (exp. (5)); depth of blasting \( H_{\text{bl}(x)} = 50 \text{ m} \); angle of open pit side \( \alpha = 40^\circ \). Substituting the initial data into formula (6), we obtain the value of the safe distance to the protected object:

\[
L_{\text{H}} = 86 + \sqrt{(50 / \sin(40^\circ))^2 - 50^2} = 145.6 \text{ m.}
\]

5. Conclusions

1. A dynamic computational analysis of the force effect from blasting operations on soils and high-pressure gas pipeline is performed. The calculation is carried out in variants, it is recommended to set the limits on the weight of explosives at the level of minimum dangerous values. The dangerous weight of explosives blasted in an open pit simultaneously, for slope structures of the mine and high-pressure gas pipeline, depending on the accepted coefficient of soil conditions, permissible vibration velocity of undeveloped soil (0.06 m/s) and shortest distance from the open pit boundaries to the protected object \( L = 625 \text{ m} \) is as follows:
   - at \( K = 300 \) it is 97.0 t;
   - at \( K = 450 \) it is 43.0 t;
   - at \( K = 600 \) it is 24.0 t.

2. According to available data, blocks of 100 blastholes are blasted in the open pit. The total mass of charges in such blocks can reach up to 26–30 t. If a number of blastholes is large, random coincidence of simultaneous actuation of different delay stages is possible, which in fact can increase total weight in the stage and cause increased vibrations. Therefore, in blasting it is recommended to design a scheme for initiation of the charges with a weight in the delay stage \( Q \) less than 1 t. When delaying each blasthole with a charge weight \( Q = 260 \text{ kg} \) at a distance \( L \) of more than 230 m from the explosion site to gas pipeline, the loss of ground seismic stability is unlikely. It should be noted that a significant number of blastholes, due to inaccuracies in the actuation of initiation means (SI), can cause actuation of more charges in the delay stage, than assumed by the initiation scheme. Therefore, to exclude interblock movements in the rock mass, it is not recommended to increase the number of blastholes in the blasted block more than twice (in regard to 100 blastholes).

3. To solve the problem of determining safe distances from blasting site in the open pit to high-pressure gas pipeline, a calculation scheme is proposed. It is based on expressions (5) and (6), which make it possible to determine safe distances to gas pipeline from any point of open-pit mine.
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