Journal of Geotechnology and Energy | vol. 41 | no. 4 | 2024 | pp. 21–26

https://doi.org/10.7494/jge.2024.41.4.6733

ARTICLE

USE OF INCLINED BOREHOLES AS INJECTION HOLES FOR FILLING BACKFILL CHAMBERS

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Date of submission:
17.11.2024

Date of acceptance:
21.11.2024

Date of publication:
30.12.2024

https://journals.agh.edu.pl/jge

Abstract: The latest environmental trends involve the use of renewable energy sources, reducing carbon footprints and minimizing the effects of past human activity. It is therefore very important to minimize the effects of the exploitation of useful minerals by eliminating mining landslides and rock voids. One of the ways to protect them is through drilling works by drilling backfill holes. The authors of the present study show the possibility of adapting diagonal drillings to drill backfill boreholes. It helps to connect voids, caverns or cavities by backfill boreholes through the injection of backfill material into them. The time of pumping the backfill material in the case of vertical and diagonal holes are analyzed.

Keywords: inclined borehole, oblique borehole, borehole injection, restorative material, backfill material

1. Introduction

The need to use land for construction often makes it necessary to pay attention to eliminating the effects of the underground exploitation of useful minerals. One method of preventing mining landslides was the so-called protective pillars, i.e. leaving unmined coal or other material under settlements, roads, industrial plants, etc. However, it should be remembered that such protective pillars should be wider the deeper they are. This is because the rocks above the selected space break at a certain slope, depending on the type of rock. With soft rocks, the slope is less, while with hard rocks it is greater. Through this, the use of protective pillars results in the loss of a large amount of material which is easy to exploit. Increasing the intensity of the exploitation of geological raw materials leads to the activation of collapse processes [1]. An effective protective measure is filling the space left by the selected raw material with another material, such as rock or sand [2]. According to the mining dictionary, backfilling is the filling of an excavation with a non-mined material (rock), obtained either on site during mining or supplied from outside [3]. Backfilling should be understood as the material with which voids are filled after the selection of usable mineral [4, 5], and therefore also in the liquidation of workings and entire mines. Drilling methods are therefore increasingly being used to backfill post-mining workings and rock voids. Backfilling, or in other words restorative boreholes, can be used to easily and quickly inject material from the surface into a specific cavern or chamber. The most common design of such boreholes is based on the lithology of the rocks to be drilled and drilling guidelines. According to the literature, the most commonly used casings for backfilling boreholes have an outside diameter ranging from 18‘ to 12’, but there are boreholes with initial pipe diameters of more than 20‘ (e.g. borehole TP-25 in the Wieliczka Salt Mine) or final diameters which are much smaller (6 5/8’ pipe column used for backfilling transport) [6, 7].

The increase in activities has meant that the direction of accessing voids by drilling methods has become dominant. Drilling techniques and technologies allow voids to be accessed which are located, among others, under existing residential or public utility buildings, flooded voids or in crisis situations – e.g. voids in a fire condition [8]. Borehole injection is increasingly widely used in the process of strengthening rock masses or filling voids. It can be used in both geotechnics and hydrotechnics. It is used to strengthen and seal the ground medium or rock mass. There are many ways of performing injections, with the basic ones being the division into classic, pressure, and high-pressure injection [9, 10].

There are two main types of borehole injection for backfilling. The first is borehole injection using the “top” backfilling technology. It is used in the case of identified voids and loosening zones, without the need to perform reconnaissance work around the borehole. Boreholes for this technology are usually drilled using the coreless technique. In terms of principles, it was developed by Geocarbon LLC. Injection work should be carried out in a control borehole in the direction from the ground surface to the bottom of the borehole [11] and it is carried out in several stages as mentioned below:
- determination of the point of drilling the control hole using the geodetic method,
- drilling the hole and carrying out the injection works,
- control of the quality of the grout,
- control of the effectiveness of filling the voids and loosening zones.

In case of limited knowledge about the location of voids and loosening zones injection using the “bottom-up” technology is used. It is characterized by coring and performing reconnaissance work around the borehole. It is also carried out in several stages [11]:
- geodetic marking of the point of drilling the control hole,
- drilling the control hole,
- control measurements,
- backfilling of voids and loose zones,
- quality control of the grout,
- control of the effectiveness of backfilling of voids and loose zones.

Currently, the following methods are used for the treatment and backfilling of mining excavations [8]:
- hydraulic backfills,
- backfills made of dry and sprayed fly ash,
- ash pulps (suspensions),
- binding slurries.

The term conditioning or conditioning works should be understood as a set of activities aimed at sealing and strengthening the building substrate by filling all voids and loosening zones as tightly as possible [11].

Among the binding slurries, we can distinguish single-component and multi-component cement dusts, cement-sand mortars, cement-dust mortars, cement-ash mortars, cement-clay mortars, cement-ash-lime mortars and slag-cement mortars [8]. Additionally, chemicals based on polyurethane organic compounds, resins, or mineral aggregates can be used as backfill material [11]. The decision on the selection of individual media to be introduced into the rock mass to achieve the intended goal must take into account a whole range of conditions: from natural, through technical, to economic [8]. Backfill holes should be effectively closed immediately after fulfilling their function [7].

2. Results

Drilling boreholes, including backfill or restorative boreholes, are primarily intended to be made as straight holes but in some cases this cannot be done. One of the main limitations of drilling the backfill borehole is the frequent case when the drilling rig cannot be positioned above the void to be filled, e.g. due to the buildings, surface infrastructure or other factors. Moreover, there is a need to perform diagonal boreholes for chambers or voids intended for backfilling which are located under highly urbanized areas. It is also recommended to drill inclined backfill holes to provide a greater visible thickness of the chamber or void compared to the vertical hole. This increases the length of the perforated section of injection pipe used to inject the backfill material and also allows for a shorter injection time of the backfill material. In backfill boreholes, making an inclined backfill hole will have a direct effect on the time required to pump the backfill material. Assuming the same volume of the chambers to be backfilled in the case of the vertical hole and the inclined hole, and taking into account that the holes made will have the same internal diameters of the submerged casing pipes, the relationship for the flow rate of pumping the backfill material in the vertical hole can be written as:

$$Q_{\max(vertical)} = \pi D H v_{kr} \tag{1}$$

and for the oblique borehole as follows:

$$Q_{\max(oblique)} = \pi D L v_{kr} \tag{2}$$

where:
- D – internal diameter of the last column of casing pipes [m],
- H – length of the perforated section of the vertical hole [m],
- L – length of the perforated section of the diagonal hole, $L = H/(\cos\alpha)$ [m],
- v_{kr} – injection velocity [m/s],
- α – angle of deviation from the vertical of the diagonal hole [°].

Table 1 shows the increase in oblique borehole length depending on the drilling angle.

Taking into account the values given in Table 1 and substituting them into the equations for the maximum pumping capacity in a vertical and oblique borehole, it can be stated that the pumping flow increases in the oblique borehole. To ensure laminar flow, the critical pumping speed v_{kr} should not be exceeded during injection. Using trigonometric relations, it can be stated that the increase in the length of the perforated hole section causes a proportional increase in the pumping flow.

Assuming the same volume of the chamber V intended for injection, when using a vertical or oblique hole, the chamber injection time is equalized. It can be written:

$$T_{vertical} = \frac{V}{Q_{\max(vertical)}} \tag{3}$$

and for the oblique borehole as follows ($Q_{max(Toblique)}$):

$$T_{oblique} = \frac{V}{Q_{\max(oblique)}} \tag{4}$$

where:
- $T_{vertical}$ – injection time of vertical borehole [s],
- $T_{oblique}$ – injection time of an oblique borehole [s],
- V – voids or chamber volume [m^3].

Taking into account the above, at a constant volume of the chamber V, the increase in the flow for the oblique borehole due to increasing of perforation length results in a shortening of the time of injection the backfilling material into the chamber. Comparing the above mentioned equations at a constant volume of the chamber, the following relationship between the injection time in an oblique well and the injection time in a vertical well is obtained:

$$T_{oblique} = T_{vertical} \cdot \cos\alpha \tag{5}$$

The relationship can be presented in a tabular form (Tab. 2) for given values of the angle of drilling an oblique hole.

Table 1. Increase in the length of the oblique borehole depending on the drilling angle

Thickness for vertical borehole [m]	Apparent thickness for an oblique borehole due to angle of drilling [m]								
	10°	20°	30°	40°	45°	50°	60°	70°	80°
H	$\frac{H}{0.985}$	$\frac{H}{0.940}$	$\frac{H}{0.866}$	$\frac{H}{0.766}$	$\frac{H}{0.707}$	$\frac{H}{0.643}$	$\frac{H}{0.500}$	$\frac{H}{0.342}$	$\frac{H}{0.174}$

Table 2. Decrease of injection time through inclined borehole in comparison to vertical borehole

Injection time for vertical borehole [s]	Injection time for an oblique borehole due to angle of drilling [m]								
	10°	20°	30°	40°	45°	50°	60°	70°	80°
$T_{vertical}$	$0.985 \cdot T_v$	$0.940 \cdot T_v$	$0.866 \cdot T_v$	$0.766 \cdot T_v$	$0.707 \cdot T_v$	$0.643 \cdot T_v$	$0.500 \cdot T_v$	$0.342 \cdot T_v$	$0.174 \cdot T_v$

*T_v means $T_{vertical}$

The chamber was analyzed at different depths calculated from the ground surface. The lowest point of the chamber floor is at a depth of $H = 10$ m, the highest point of the chamber floor is at a depth of $H = 1.5$ m and the maximum vertical length of the perforated section is $H = 8$ m. The length of the perforated section making the chamber accessible for injection can be adjusted by changing the angle of the hole (Tab. 3).

Taking into account the increase in the length of the perforated section according to Table 3, it is possible to determine the injection time of the chamber through the diagonal hole made. The chamber to be backfilled has a defined volume. Assuming a constant value of the injection flow of the backfilling material, the pumping time through the vertical hole is determined.

Assuming an equal pumping rate of the backfill material through the vertical hole and the diagonal hole, the time for pumping the backfill material through the diagonal hole will be determined according to the time equation. It is found that the pumping of the material through the completed diagonal hole is carried out in a shorter time compared to the vertical hole, as shown in Figure 1.

Table 3. Dependence of the length of the perforated section of the hole on the angle of its execution

Thickness for vertical borehole [m]	Apparent thickness for an oblique borehole due to angle of drilling [m]								
	10°	20°	30°	40°	45°	50°	60°	70°	80°
8	8.12	8.51	9.23	10.44	11.31	12.44	16	23.39	46.07

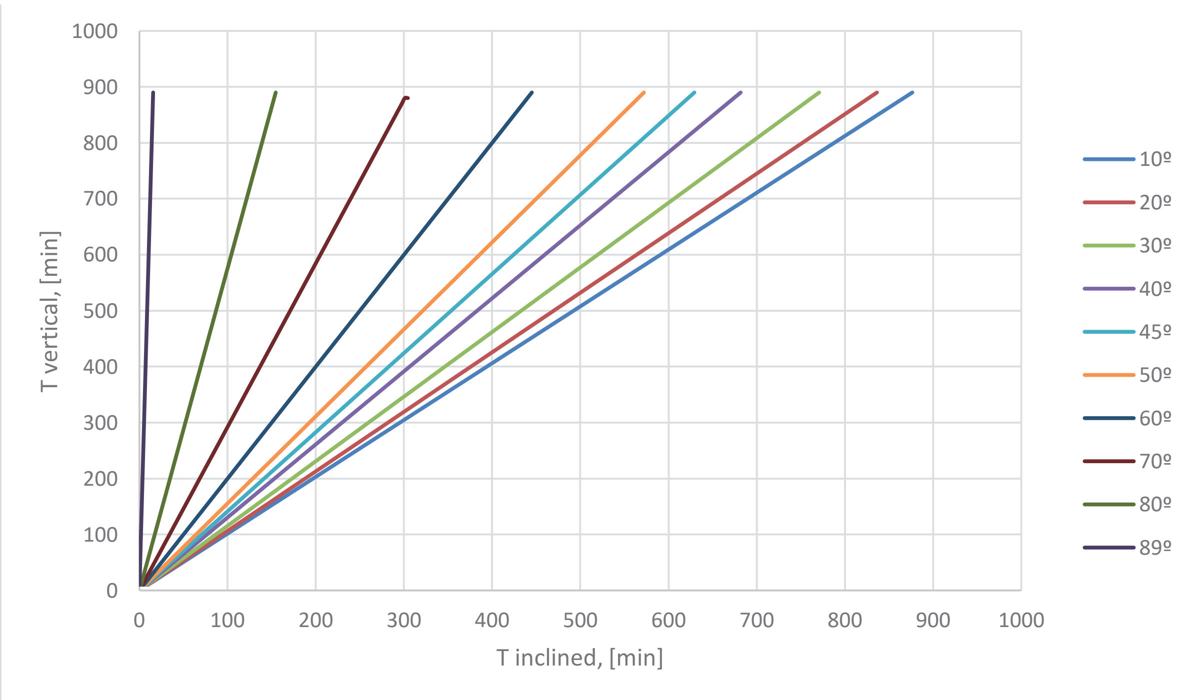

Fig. 1. Influence of the angle of the inclined borehole on the injection time of the backfill material compared to the injection time through a vertical borehole

The relationship between the pumping times of the backfill material through the oblique borehole and the pumping time through the vertical borehole of the same chamber is shown in the range of angles 10–89° at which an oblique borehole can be made. The situation where a diagonal hole is made at an angle of 89° will be rare, but cannot be excluded. At present, a number of scientific papers show that solutions for drilling small-diameter holes using hydraulic nozzles from base holes [12–14] are being used more and more frequently. Despite the small inside diameter of such holes, in the range of 50–70 mm, they can be easily adapted to make small-diameter injection channels when space is limited for drilling with standard equipment for shallow drilling up to 200 m vertical depth. The decrease in pumping time of the backfill material through an 89° inclined hole is significant. Since cos 60° = 0.5 and taking into account the above equations to facilitate quick calculations in the field, the pumping time through a diagonal hole made at an angle of α = 60°, will always be about half of the pumping time through a vertical hole.

3. Conclusions

- Diagonal or inclined boreholes have a drilling angle other than vertical and a direction other than standard vertical boreholes from top to bottom. They can be drilled from the ground surface, from the interior of buildings/infrastructure and from the excavations of underground and opencast mines.
- The drilling of a diagonal hole is usually more difficult and exposed to drilling failures and complications compared to vertical drilling. This is strictly connected with an angle of internal friction each drilled lithological layer.
- The use of inclined boreholes will lead to an economic gain by reducing the time it takes to inject the backfill material into the infilled chamber or mine workings void.
- The pumping time through a diagonal hole drilled at an angle of α = 60° will always be about half that of a vertical hole.

Author contributions: Conceptualization PT and AR, formal analysis TK, methodology TK, writing – review and editing, writing – original draft preparation, and investigation, PT and AR and TK, supervision, validation, project administration, PT. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors of this paper declare no conflicts of interest.

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