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Assessment of drilling deviations in underground operations

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ABSTRACT

At present, modern jumbos equipped with MWD (Measure While Drilling) provide the position of the blastholes collar and, from the drill length and the azimuth and inclination angles (monitored outside the blasthole), the theoretical end position of the blasthole. Since the trajectory of the hole during the drill is not measured, deviations are not accounted with the result that the actual spatial position of the blasthole is unknown. This paper investigates the quality of the drilling in underground blasting operations with a view to quantify the distance of the position assessed by the MWD system with respect to the actual end position of the blasthole logged. For that, a Pulsar Micro Probe Mk3 has been used to measure the actual trajectory of several production blastholes, drilled in semi-automatic mode, by measuring inclination and azimuth values at 1 m intervals. The results indicate significant deviations between the actual end position of the blastholes and the end position given by the MWD system. Deviation measurements are compared with the MWD parameters. This points out that possible disturbance zones in the rock, indicated by peaks and drops in the variability of the rotation pressure and in the signals of feed and hammer pressure, are correlated with changes in the blasthole trajectory.

1. Introduction

Drilling and blasting is a well-known technique used for rock excavation in tunnelling or underground civil works. In it, drilling operation is one of the critical stages of the overall excavation process with major influence in the efficiency of the next stages, such as blasting, scaling, loading, hauling and support operations. In underground constructions, drilling is normally carried out by top hammer rotary-percussive jumbo drills. Generally, these jumbos bring the possibility to monitor the information of sensors installed along the mechanisms of the feeder and the boom to record digital signals of the parameters involved in the operation. The Measurement While Drilling (MWD) technique is a drill monitoring system that collects operational drilling data at predetermined length intervals along the blasthole (Schunnesson, 1997). This technology allows to log not only real time information of the rock mass condition while drilling, but it also brings the possibility to record the collaring position of the blasthole and, from the length of the drill rod and the azimuth and inclination angles of the boom, its theoretical end position inside the rock mass.

Nowadays, modern jumbos like those manufactured by Atlas Copco, Sandvik and AMV include drilling automation, e.g., ABC (Advanced Boom Control), iREDES and Bever Control, respectively, to optimize drilling. As an example, the drill rig of jumbos manufactured by Atlas Copco jumbos has three operational levels of automatization: basic, regular and total (Nord and Appelgren, 2001; Atlas Copco, 2010; Östberg, 2013; Navarro et al., 2018a). The basic level authorizes only the manual performance of both positioning and drilling. The regular level allows to follow a predesigned drill plan with manual control of the boom whereas drilling is automatic. The total level enables the use of a predesigned drill plan and to switch collaring and drilling between manual (manual collaring and drilling), semi-automatic (manual collaring - automatic drilling) and fully-automatic (automatic collaring and drilling) mode.

Based on the MWD records, manufacturers have developed their own software (Tunnel Manager - Atlas Copco, iSURE - Sandvik and Bever Control in cooperation with AMV) as a tool for planning, management and evaluation of drill parameters. From the MWD records, blastholes can be represented in 3D maps and rock properties such as hardness and fracturing are inferred and displayed (Atlas Copco, 2017; Sandvik, 2017; Bever Control, 2017). Although these software packages show the position of the blastholes, this is only a theoretical representation since the actual position is not measured. Four variables mainly influence deviations during the drilling (Östberg, 2013): (i) setting out, (ii) collaring and alignment, (iii) drill rod deflection and (iv) rock structure.

Blasthole positioning is monitored from sensors (inclinometers-accelerometers) installed along the boom and thus, outside the blastholes. Since the boom remains still during the drill, it normally measures

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constant values of its direction. However, the actual path inside the rock is not measured, due to neither the drill rod nor the bit are equipped with any sensor. This suggests an unknown error of the bottom hole position in relation to the design position (given by the MWD system). Olsson (2010) analysed this error for the contour blastholes by measuring, with a total station, the end position of the half cast contour holes when they were visible. He determined a mean deviation value of 11.6 ± 6.8 cm (mean ± standard deviation). To the authors knowledge, no additional data on deviations of production blastholes in tunnelling has been published.

Drill deviations may generate a non-uniform explosive charge concentration: excessive proximity between two blastholes may increase the specific charge (or volume charge concentration) in this zone, whereas a higher distance between them may reduce it, resulting in problems with rock breakage, fragmentation and pull. They may also induce problems in the perimeter excavated. Outwards deviations create an excessive over-excavated zone generating short-term stability problems around the perimeter of the excavation. This also increases production costs due to the retrieval of the extra material blasted and the need of a sturdier primary supports. Inwards deviations cause under-excavation zones in the perimeter, requiring a more intensive scaling to fulfil the pay-line requirements.

There is a large number of studies focused on the geological and geo-mechanical interpretation of the MWD (Teale, 1965; Scoble et al.,1989; Schunnesson, 1996, 1997, 1998, 2011; Schunnesson and Kristoffersson, 2011; Liu and Karen Yin, 2001; Kahraman et al., 2016; Peng et al., 2005; Tang, 2006; Hjelme, 2010; Naeimipour et al., 2014; Hatherly et al., 2015; Leung and Scheding, 2015; Ghosh, 2017); however, the effect of the rock structure, determined through the MWD data, on the drilling deviation has not been studied.

A thorough description of the jumbo navigation and positioning is presented, in order to get a deeper understanding of the different stages required for an accurate drilling. In order to assess the hole deviation, a Pulsar Micro Probe Mk3 has been used to measure the actual end position of five production blastholes, drilled with an Atlas Copco jumbo, by measuring inclination and azimuth values at 1 m intervals of the trajectory followed by the blasthole. The results are compared with the end position provided by the MWD system and the error between this and the actual end position is estimated. Deviation measurements are also compared with MWD parameters in order to assess the influence of the rock structure in the drilling path.

2. Jumbo navigation and blasthole positioning

Jumbo navigation is the first operation before starting a new round to follow the correct tunnel layout. The operation is carried out in two steps: jumbo positioning and alignment with the tunnel axis.

The first operation consists of measuring the exact position of the jumbo inside the tunnel to create an absolute coordinate system. For this purpose, the jumbo has a laser scanner on its front side. The position of the jumbo is calculated by trilateration, measuring distances from the laser scanner to target points (with known coordinates) located along the wall side of the tunnel (Fig. 1a). The absolute coordinates X_{abs}, Z_{abs} obtained are given, in this case under study, in the EUREF 89 Norwegian Transverse Mercator (NTM) projection and the absolute coordinate Y_{abs} is measured as the height above sea level.

The second operation consists on aligning the drill rig with the tunnel axis (i.e. the perpendicular line to the face of a new round). The laser scanner points to the free face in the direction of the tunnel axis and two targets are aligned along one of the booms of the jumbo. For the alignment, the boom rotates until the laser beam passes through both targets (Fig. 1b). At this stage, the drill rig creates a tunnel reference system ($\vec{x_t}$, $\vec{y_t}$, $\vec{z_t}$) with one axis parallel to the tunnel axis and the other two in the plane of the tunnel free face (Fig. 1b). Finally, the chainage (ch) inside the tunnel of the new round is measured as the distance from the laser scanner to the free face. This ch is taken as reference plane of the collaring depth position of the blastholes. Negative depth values are assigned to measures behind this plane and positive values, to measures ahead of this plane (Navarro et al., 2018b).

The former operations make the jumbo to be oriented by three angles (γ, θ, ω), according to the horizontal ($\vec{x_t}$, $\vec{z_t}$) and vertical ($\vec{z_t}$, $\vec{y_t}$) directions of the tunnel axis and the ($\vec{x_t}$, $\vec{y_t}$) rotation of the free face, respectively. To calculate the position of the blastholes, the drill rig rotates the planes formed in the tunnel reference system (X_tZ_t, Y_tZ_t, X_tY_t), to create a drilling reference system defined by two vertical planes Y_dZ_d, X_dY_d and a horizontal X_dZ_d plane, as correction of the jumbo orientation by angles θ, ω and γ, respectively. Fig. 2 shows the rotation carried out by the drill rig over axes $\vec{y_t}$ (left graph), $\vec{x_t}$ (centre graph) and $\vec{z_t}$ (right graph) to define the drilling reference system of axes ($\vec{x_d}$, $\vec{y_d}$, $\vec{z_d}$). Graphs in red correspond to horizontal (X_dZ_d) and vertical (Y_dZ_d, X_dY_d) planes in the drilling reference system and graphs in black to the rotated planes (X_tZ_t, Y_tZ_t, X_tY_t) according to the tunnel axis or free face orientation.

Blasthole position measured in the drilling reference system is defined by three spherical coordinates (see Fig. 3): blasthole length (l_b), azimuth (angle of the horizontal $\vec{x_d}$ axis and the hole projection in the X_dY_d plane) or lookout direction (L_D) and inclination or lookout angle (L_I). The two later are logged by sensors installed along the boom outside the blasthole and the blasthole length (l_b) corresponds to the drill rod length introduced in the hole. The inclination angle varies between 0 and 90° both for holes drilled upwards or downwards so that the azimuth is between 0 and 180° for holes drilled upwards and between 0 and −180° for holes drilled downwards. Fig. 3 shows the theoretical (X_F, Y_F, Z_F) projections of a blasthole (drilled downwards) in the drilling reference system; they are (Navarro et al., 2018b):

$$X_F = l_b \cdot \sin(L_I)\cos(L_D) \tag{1}$$

$$Y_F = l_b \cdot \sin(L_I)\sin(L_D) \tag{2}$$

$$Z_F = l_b \cdot \cos(L_I) \tag{3}$$

Once the boom is placed in the required position and before starting to drill, the drill rig registers, in the drilling reference system, the collaring position of the blasthole and the azimuth (L_D) and inclination (L_I) angles of the boom (see Fig. 3). The end coordinates of the blasthole are theoretically calculated by adding, to their collaring coordinates, the result from Eqs. (1)–(3).

3. Data overview

The study has been developed in the underground extension work of the municipal wastewater treatment plant in Oslo, Norway. The facility is composed of five caverns, a main access gallery of about 850 m length and other sections. The construction was excavated by drill and blasting in competent rock mass, composed by gneiss with small tonalite and quartzite intrusions. This study is focused in the fifth cavern of 460 m^2 section (20 m width × 23 m height) and around 180 m length. The excavation of the cavern was divided in two sections, being the upper one (20 m width × 10 m height) firstly developed by horizontal parallel holes with an advance of 4.5 m/round and secondly the bottom section (20 m width × 13 m height) by vertical holes through bench blasts. The excavation of the upper section was done by dividing the blasting front in two sections, right and left (10 m width × 10 m height, each), following the next drilling and blasting procedure: three blasts in the left side of the section and next, three blasts in the right side to start over the cycle.

Drilling was carried out by a three-boom jumbo XE3C, manufactured by Atlas Copco, with percussive-rotary top hammer drilling mechanism, working in semi-automatic ABC total system. Data comprises production face blastholes of short length (5–5.5 m), drilled by using only one rod of 5.5 m length and 38 mm diameter and a bit of 46 mm diameter. A 3.18 revision control system (RCS) was installed in