1. Introduction

Drill plan design and the accuracy of drilling equipment have a significant role in the overall control and productiveness of a tunneling construction site. Effects cover many sectors of the tunneling cycle through the quality of excavation. The profile of the excavated tunnel can be controlled by blast management and correct placing of drill holes. A good excavated profile within the limits of the excavation tolerance range creates the basis for effective drilling of the next round. Achieved accurate and smooth profile also makes the need for support works smaller and potentially reduces the amount of required sprayed concrete.

Thorough navigation and caution in phases of drilling cycle are factors influencing the accuracy of the drilling equipment. The importance of these factors has to be realized and observed by all involved in the process.

It is essential to be conscious of the fact that the ability of a drilling jumbo to drill the hole into the planned location, direction and length is a feature that the whole economical excavation is based on. The iSURE (intelligent Sandvik Underground Rock Excavation) software tool offers a project tree approach combining all tunnel plans related in project. A tunnel plan, in turn, combines a curve table, tunnel profiles, drill plans, lasers and data collection files, all of which can also be controlled separately. A complete tunnel plan or drilling pattern can be transferred to i-series jumbo. Transfer to TDATA/TCAD hardware is also supported.

2. Basics of Drill Plan Design

Drilling pattern design for DATA-controlled drilling unit has traditionally included steps related to full automatic drilling cycle such as positioning of holes, determining directions for holes, defining the boom sequences and roll-over angles. Some general steps in the design process are still the same but many improvements and new features are included in the process.

The aim of the design is to provide needed information for the drilling unit to be able to drill a whole round in automatic mode under supervision of the operator. Normally the first step has been designing of theoretical profile which is the profile that the finished tunnel should have. This is commonly determined by the client. This step has been followed by determining the locations of holes and by defining separate directions for each hole. After the information concerning locations and directions of holes has been defined some functional settings for the drilling machine has to be determined. Most commonly this step includes designing the sequence for drilling booms i.e. the order in which the holes will be drilled for each drilling boom and determination of roll over angles i.e. how the boom is positioned while drilling the hole.
In addition to drilling pattern design some information related to tunnel line has usually been provided e.g. to be able to navigate the rig into the tunnel and to be able to fix the rig’s coordination system to the tunnel coordinate system.

Modern system for drilling pattern design has been taken into a new level of thinking. Consideration of hole locations is made in the most critical part of the drilling pattern i.e. in the end of the round where the blasting initiates. Taking design into the blast plane also enables burden calculation and parameterization of the design. By using parameter based blasting modeling aim is to optimize the drilling pattern and consequently achieve better quality in excavation resulting savings in overall costs.

2.1 Basic terms and definitions used in design

One step during the design process is to determine the length of the drilling pattern. This is defined to be the distance between the navigation and the blast plane. Length of the drilling pattern is dependent on the feed length of drilling jumbo which also specifies the maximum length of the drill steel and hence maximum length of the drilled hole. It is possible to specify varying depths for different hole classes in the pattern to be able to shape the round end (Fig. 1). By controlled round shape benefits such as optimized blasting effect, maximized pull-out, better collaring of next round and better loadability can be gained. Different hole classes in the design have been categorized in five different types: contour-, aidrow 1-3- and field type of holes (Fig. 1).

As mentioned above the design for hole locations is based on parameter based blasting modeling i.e. burden calculation. Burden V [m] is defined to be the shortest distance from the hole to be blasted to an open space which also could be the space created on a blasting just moment ago (Fig. 2). The burden is dependent on the strength of the explosive, rock factor, inclination of holes and spacing between the holes. The maximum allowed burden is considered at the end of the round where the situation is most critical.
The spacing between the holes $E \text{ [m]}$ is the distance between adjacent holes in the same hole class or in the same element i.e. the distance between the holes in the contour for example (Fig. 2). In theory, better quality of excavation will be achieved if the spacing in the contour holes is reduced. In practice, this is not always the situation due to scattering of drilling and drill hole deviation. Too short distance between the holes may lead to an uncontrolled situation where explosion gases may burst into the next hole blowing out the explosives or compress the hole so that the explosion can not take place.

![Figure 2. Hole positioning at the blast plane. Red profile is representing the lookout profile. Burden and spacing also represented.](image)

The ratio between spacing and burden is typically in the range of 0.8 for the profile i.e. contour holes. In such case the explosion in the contour holes breaks the rock between the holes before pushing rock towards the center of the profile.

Specific charging $q \text{ [kg/m$^3$]}$ is defined to be the needed amount of certain explosive (with a certain strength kg/m) to loosen a certain volume of rock.

The average degree of packing $I \text{ [kgREF/m]}$ is used in the calculation to be able to use different explosives during the design i.e. the explosives are comparable to each other. The strength is specified as a proportion to a known reference explosive such as dynamite or ANFO as an example.
2.2 Burden calculation

When blast is considered from the charge initiation point of view (starting from the middle of the drill plan or where the cut is located) it could be stated that the most optimal location of the next charge row is such that has enough power to break the rock to the open space just created by the previous holes initiated. Additionally enough power is needed to move the expanded rock mass and to create an open space for the next charge row to be blasted. To be able to utilize burden calculation in drill plan design, the situation has to be considered at the end of the round i.e. at the blast plane. In practice the hole endings are designed and displayed at the blast plane for calculation purposes. By this procedure the calculation can be performed in 2D (Fig. 2).

3. Drilling pattern design

Drilling pattern design has a direct influence on the employment of time of a drilling rig. Roughly, the employment of time for a drilling cycle consists of setup time and navigation of the rig, drilling of holes according to drill plan, boom movements between holes and some auxiliary time after drilling. If the drilling pattern is properly designed, the employment of time can be affected. By the shape of the round end the collaring of a new hole can be influenced. Equal drilling time for each boom is important i.e. avoidance of standing time of booms. This can be controlled by proper designing of drilling sequences. By sequence design possible danger of booms crashing each other can be avoided as well. Appropriate design for aligning the holes, drilling sequences and roll over angles means that the accuracy of the automated rig and repeatability of the designed pattern is fully applied. The selection of cut type and design of the cut have an extensive impact on pull out and evenness of the shape of the round end. The design and type of cut also determines whether there is a need to change a reaming bit during round drilling and if relatively slow reaming has to be done. The amount of drill holes in drilling pattern has an effect on pull-out, fragment size and quality of excavation. Drilling time of one round can be influenced by length of the round. Typically, in time-wise, it is productive to drill as long rounds as possible but in this case possible limitations in excavation and in vibration control near populated areas have to be considered.

Essential part of tunnel worksite management is predictability of the excavation cycle. Not only to be able to be systematically prepared that the needed capacity is available in correct place at correct time but also because possible limitations in blasting can be considered.

In a large construction site the fixed costs form a significant portion of the total costs. This means that every delay in the cycle or lost round leading to site idling is very expensive. The drill plan design substantially affects the drillability of the pattern. The design of direction angles, drilling sequence and roll over angles can ease the drilling of the pattern, which equals to decreased need of manual boom alignment movement. Mechanical failures of a rig can be avoided as well by the criteria referred to above. All this means less deviation in round drilling time, which reflects as better predictability of the cycle.

At its best, the role of drill plan design software in a tunnel construction worksite is a tool for total excavation process management.

4. Different working phases in design

In the software one tunnel project can be processed at a time. A project tree approach is used for project management. Tunnel project consists of tunnel lines and navigation sets. Tunnel line includes curve table points, theoretical profiles, drilling- and bolting patterns, tunnel lasers and data collection files. Curve table
comprises information such as peg numbers, coordinates and cambers and all this can be imported from MS Excel for example. Theoretical profile can be designed manually by using drawing tools but also a selection of standard profiles is included in the software. Designed profile is defined for a certain peg number range. Different profiles may be used for different peg numbers and interpolation from profile to another is managed by the software (Fig. 3).

Figure 3. Picture showing a tunnel project containing a tunnel plan for the access tunnel and for the main tunnel. Profile expansion and an interpolation from profile A to profile B shown in the main tunnel.

Subsequently locations for tunnel lasers can be defined. In the navigation sets some information concerning the navigation is prefilled. This action decreases some manual work needed on the rig. Drilling pattern can be designed for the theoretical profile that was defined in previous step. There is a possibility to make the design in the navigation plane or in the blast plane as described above. Blast plane design is recommended way since all the features and strengths of the software will be then utilized. Design for a predetermined profile starts by defining some assistance profiles (Fig. 4). These profiles include start and end (lookout) profiles, minimum and maximum tolerances for the excavation and maximal allowed fracture zone.
Some parameters for the software have to be defined before the actual positioning of holes can be made. For calculation purposes information such as list of used explosives and their individual degree of charge [kg/m] plus degree of charge in reference to some commonly used and known explosive e.g. dynamite or ANFO [kgREF/m] needs to be determined. Additionally the size of fracture zone for each explosive has to be defined.

As described above the design is made in the blast plane i.e. in the end of the round. Another difference compared to present design methods is that the design is started from the contour and thereafter gradually moved towards the center of the drill plan. Reason for this is the logic used in the calculation. Based on the information given to the software it automatically defines the most optimal place for the next row of holes. So for example when the blasting has reached 1\st\ aidrow, the contour holes are charged heavily enough to break the rock in front of it.

Hole positioning is made for one element at a time i.e. contour, 1\st\ aidrow, 2\nd\ aidrow, etc. In practice the first step is to define a few so called position master holes. Purpose of these position master holes is to separate elements like wall, roof and bottom from the current profile. After position master holes have been placed it is possible to specify the element between two position master holes and bind the parameters used for the calculation purposes for specified element (Fig. 5).
Needed amount of aidrows (maximum 3) are added into drill plan. The cut is designed and placed manually by the user and finally some field elements can be added if needed. If applicable cut exists in an existing drill plan there is also a possibility to import it.

Next phase in design is to direct the holes. By this an individual direction and angle for each hole can be defined. Different procedures are available for the user in this phase.

After directing holes the drilling sequence needs to be defined. Drilling sequence specifies how many holes each boom will drill and in which order. Carefully designed sequence makes the round drilling optimal in order to utilize the booms effectively. Also overlapping between booms and possible crashes can be avoided.

Roll-over angle, which is specified as next, defines the angle of the roll-over joint in which the hole will be drilled. This is needed to be able to drill and place the boom effectively and smoothly.

The order of detonation is an important part of the excavation design even though this information is not needed for the drilling pattern design. However the software offers a possibility to plan the order of detonation. The information can be utilized as guidance for charging crew and for calculating momentary amount of explosives for example. There is also possibility to include surface delay detonators in the design to be able to ease the charging design in urban areas or areas where vibrations are strictly limited and controlled (Fig. 6).

![Figure 6. Features of detonator design and explosion summary.](image)

Final stage is to define a hole type for each hole. By setting this info the drilling machine will use the preset parameters bound to the hole type for drilling each hole. This feature increases the accuracy of drilling when for example lower pressure levels are used for drilling contour and cut holes.

When design is ready the software will run a check list to be certain that each hole has a charge ( if not specified as a reamer hole), is part of a drilling sequence, has a roll-over angle defined, is part of a detonating order and has a hole type defined. Also some checking is made concerning the detonator design especially if surface delay detonators are used.

Software offers also possibility to generate printable documents from the plans. Printouts can be used as legitimate documents. Nevertheless it has to be noticed that reports related to explosives are created on
the basis of the explosive type defined in the charge table and bottom and column charge related to corresponding explosive type. Therefore the reports are only theoretical.

Complete drill plan can be transferred to a drilling jumbo via memory stick. Additionally related information such as tunnel line, lasers and bolting plans can be transferred to jumbo.

Depending on the project the life cycle of a drilling pattern may be fairly long. However due to possibility of rapidly changing conditions and rock type it is important to be able to make changes to the drill plan fast and efficiently. This way the pattern can be adjusted to suit current circumstances and the results in excavation, in quality- and in cost-wise, can be optimized while the tunnel advances and the rock conditions vary.

5. Conclusion

An accurate tunnel line requires accuracy both in drilling and blasting. To be able to excavate an accurate tunnel profile the general geology of the area and the mechanical properties of the rock should be known and the excavation should be designed according to their challenges. A good result usually requires many blasted rounds and improvement of the drilling pattern should be continued after every round.

The design of a drilling pattern starting from the end of the round is a new and revolutionary way of designing an economical drilling pattern excavation wise. A substantial part of the design is to find the needed specific charging values for each section of the drilling pattern. Once these values are found for a certain rock type, the optimization of the drilling pattern and appliance to other drilling patterns go smoothly.

Only seamless interaction of drilled pattern, charged explosives and detonator delays can provide optimum excavation results in terms of round bottom and profile control, drilled meters, powder factor, pull out rate, vibration control, tunnel advance and costs. Therefore, an overall approach is an absolute necessity for a tunneling project when the focus is on excavation quality.

References