Advanced Blasting Techniques (MND410)

Assignment | Date of Submission – 31.03.2023

Building an executable file that can estimate the rate of penetration of different mechanical drilling systems

Assignment Overview:

Building an executable file using the C programming language to estimate the probable rate of penetration for the following systems of drilling, considering the required algorithms falling under each of them -

1. Rotary Percussive Drilling System:
    a) USBM, 1969
    b) Norway, 1979
    c) Benaola, 1985
2. Rotary Drilling System:
    a) Bauer and Calder, 1967
    b) Bauer, 1971
    c) Calder and Workman, 1994

The number of algorithm options should be showcased to the user, and the user should be able to select his/her favorite algorithm under their favorite method for estimating the ROP. Thereafter, the user shall be required to provide the input parameters necessary for that corresponding algorithm. For such input parameters, the order of units has to be mentioned. Finally, user will be able to see the result.

Objectives:

- A basic tool for quickly estimating the ROP (Rate of Penetration) with minimum error.
- No requirement of manually determining the properties by analyzing the concerned empirical graphs based on given parameters. The program automatically determines such values very precisely and shows user the most probable result.
- This program is built, keeping in mind that user will provide the parameters' input in common units. However, such units have been mentioned.

Supporting Tools:

- plotdigitizer.com for locating points on the given graphs.
- dcode.fr for finding equation for a set of different points.

Algorithms involved

User will be able to choose between two drilling methods i.e., Rotary Percussive drilling and Rotary drilling. For this, I have indicated alphabets ‘a’ and ‘b’ against the respective types of drilling. User will enter the corresponding alphabet adjacent to the type.

Upon entering the choice in the form of required alphabet, the next stage shows the list of different methods available thereunder to find ROP (Rate of Penetration). Again, user will have to enter the adjoint number corresponding to the method of interest.

Once the user decides the method under the selected drilling system, it will be required to enter various parameters involved in that method. Eventually, the system will show the result in the form of the most probable estimation of ROP. It will be based on the input provided by the user.

Pseudo Code (Preliminary)

- Start
- List the two types of Drilling (Rotary Percussive & Rotary)
- Get user’s choice between the two.
    - List various methods under each of the drilling type.
    - Get user’s choice among those methods.
        - Let user enter various parameters concerned in the selected method.
        - Print the result.
- End

```
Mechanical Drilling types commonly used in mines:
a - Rotary Percussive Drilling
b - Rotary Drilling

Type for which you want to find the ROP (Enter the adjacent alphabet) -
Your choice? a

Different methods for Rotary Percussive drilling:
1 - USBM, 1969
2 - Norway, 1979
3 - Benaola, 1985

Your selected method for estimating ROP (Enter the corresponding number. For example, 2 for Norway, 1979): 2

Norway, 1979 -

Brittleness index (S20 value) of the rock: 77
Siever's J value (Sj): 60

Drilling rate index of the rock is close to 89.493927 and it has a high drillability.
```

Figure 1: Sample Output

Once the user has decided to go with a particular ROP estimation method, there lies further algorithms in those methods in different way, and not just input and output things. These algorithms for each method are discussed below:

A1. USBM, 1969 –

USBM method

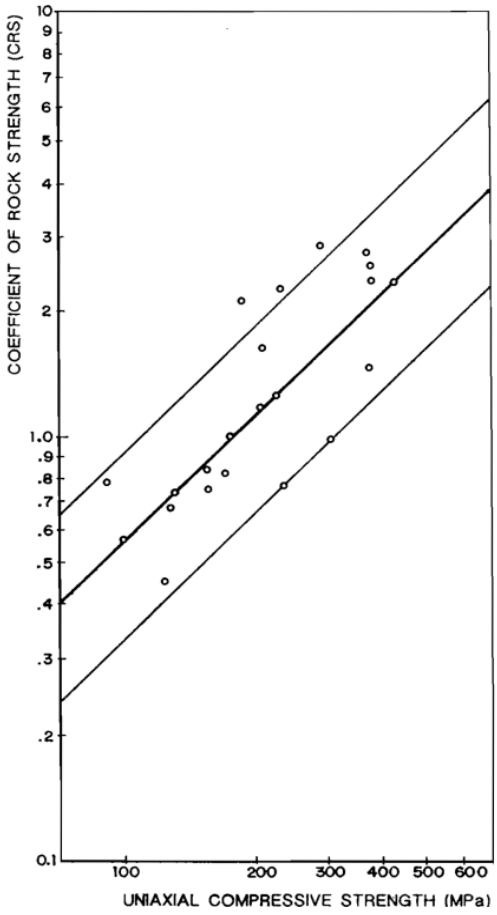
$$ROP = \frac{48 \times P_M \times R_e}{\pi \times D^2 \times E_\nu}$$

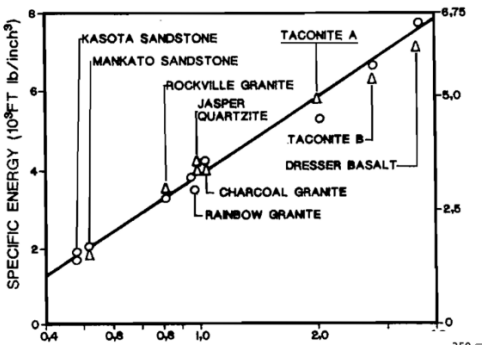
Where, ROP is in cm/min; P_M is drill power in $kg\ m/min$; R_e is the transmission ratio; D is the diameter in cm; and E_ν is the specific energy in $m\ kg/cm^3$.

Common parameters given in the problems are:

- Drill Power
- Drill hole diameter
- Uni-axial Compressive Strength of the rock
- Energy transmission Output

The specific energy can be derived with the help of UCS out of the graphs available empirically:





Graph of CRS vs UCS :

$$CRS = \begin{cases} 0.00575945\,(UCS) - 0.036927 & 10 \le UCS < 220\ MPa \\ 0.00789412\,(UCS) + 0.290636 & UCS \ge 220\ MPa \end{cases}$$

→ Here, I've considered only middle and upper straight lines, because for the lower line, the range of UCS is not clearly distinguished, and also there are not enough number of empirical observations lying near the third line.

Graph of SE vs CRS :

$$SE = \left[1.78834\,(CRS) + 1.60241\right] \times 8.437 \ \frac{m\,kg}{cm^3}$$

So,

$$SE = \begin{cases} (0.0102998\,(UCS) + 1.53637) \times 8.437 & 10 \le UCS < 220\ MPa \\ (0.0141173\,(UCS) + 2.122166) \times 8.437 & UCS \ge 220\ MPa. \end{cases}$$

Pseudo Code (USBM, 1969)

- Start
- Let the user enter parameters such as bore hole diameter, drill power, UCS, and energy transmission output.
  - Coefficient of rock strength function in UCS is determined firstly, and with its help, specific energy function is determined in term of UCS.
- Apply the formula of USBM.
- Print the result.
- End

```
if(d==1){
  printf("\nUSBM, 1969 -\n\n");
  printf("Drill power in Kg*m/min: ");
  scanf("%f",&P);
  printf("Blast hole diameter in cm: ");
  scanf("%f",&D);
  printf("Uni-axial compressive strength of rock (MPa): ");
  scanf("%f",&UCS);
  printf("Energy transmission output (0.6-0.8): ");
  scanf("%f",&R);
  if(R>=0.6&&R<=0.8){
     if(UCS>=10&&UCS<=220){
     printf("\nRate of Penetration for the given condition is %f cm/min.",
            15.2789*(R*P)/(D*D*(0.0102998*UCS+1.53737)*8.437));
     }
     else if(UCS>220){
      printf("\nRate of Penetration for the given condition is %f cm/min.",
             15.2789*(R*P)/(D*D*(0.0141173*UCS+2.122166)*8.437));
     }
     else{
      printf("\nWarning: Enter the legal value of UCS!");
     }
     }
  else{
       printf("\nWarning: Enter the energy transmission output in valid range!");
       }
```

Figure 2: Code (USBM, 1969)

```
Mechanical Drilling types commonly used in mines:
a - Rotary Percussive Drilling
b - Rotary Drilling

Type for which you want to find the ROP (Enter the adjacent alphabet) -
Your choice? a

Different methods for Rotary Percussive drilling:
1 - USBM, 1969
2 - Norway, 1979
3 - Benaola, 1985

Your selected method for estimating ROP (Enter the corresponding number. For example, 2 for Norway, 1979): 1

USBM, 1969 -

Drill power in Kg*m/min: 7782
Blast hole diameter in cm: 12
Uni-axial compressive strength of rock (MPa): 300
Energy transmission output (0.6-0.8): 0.7

Rate of Penetration for the given condition is 10.775918 cm/min.
```

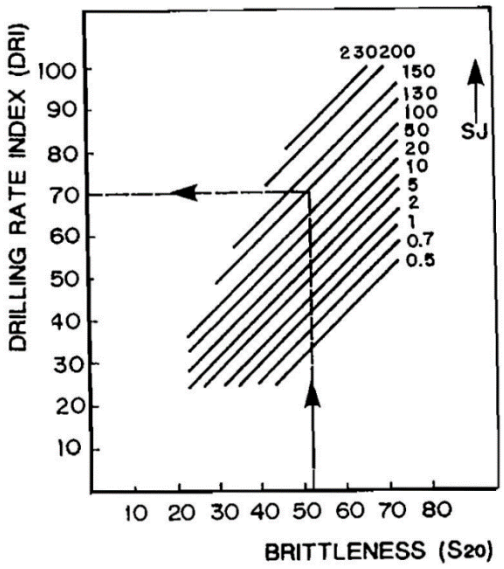
Figure 3: Output (USBM, 1969)

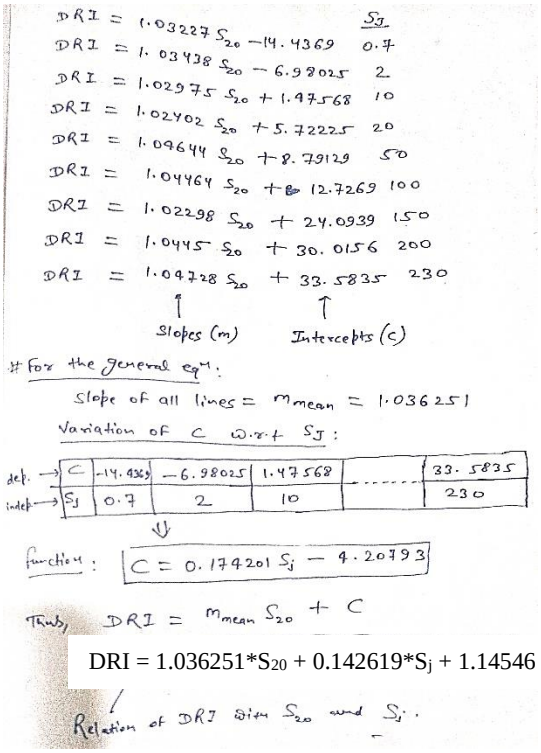
A2. Norway, 1979 –

Parameters given in the problem:

- Brittleness index (S_{20}) of the rock
- Siever's J Value (S_j) of the rock

Drilling rate index is finally determined in this method based on the empirical nomogram:





- In the nomogram, the slope of line is same for all the Sj values.
- For the generalized intercept value in the graph of DRI vs S_{20}, intercept (C) is plotted against each Sj value, and a linear relation is extracted between C and Sj.
- The generalized value of slope is taken to be the average value of all the slopes.
- Finally, the relation of DRI with S_{20} and Sj is determined.

Pseudo Code (Norway, 1971)

- Start
- Let the user enter parameters such as brittleness index (S_{20}) and Siever's J value (S_j).
- Use the relation of DRI with S_{20} and S_j, determined with the help of the nomogram.
- Print the result.
- End

```
else if(d==2){
  printf("\nNorway, 1979 -\n\n");
  printf("Brittleness index (S20 value) of the rock: ");
  scanf("%f",&S20);
  printf("Siever's J value (Sj): ");
  scanf("%f",&Sj);
  DRI=(1.036251*S20)+(0.142619*Sj)+1.14546;
  printf("\nDrilling rate index of the rock is close to %f", DRI);
  if(DRI<=30){
      printf(" and it has a low drillability.");
  }
  else if(DRI>30&&DRI<60){
      printf(" and it has a medium drillability.");
  }
  else{
      printf(" and it has a high drillability.");
  }
}
```

Figure 4: Code (Norway, 1971)

```
Mechanical Drilling types commonly used in mines:
a - Rotary Percussive Drilling
b - Rotary Drilling

Type for which you want to find the ROP (Enter the adjacent alphabet) -
Your choice? a

Different methods for Rotary Percussive drilling:
1 - USBM, 1969
2 - Norway, 1979
3 - Benaola, 1985

Your selected method for estimating ROP (Enter the corresponding number. For example, 2 for Norway, 1979): 2

Norway, 1979 -

Brittleness index (S20 value) of the rock: 53
Siever's J value (Sj): 52

Drilling rate index of the rock is close to 63.482952 and it has a high drillability.
```

Figure 5: Output (Norway, 1971)

A3. Benaola, 1985 –

Pseudo Code (Benaola, 1985)

- Start
- Let the user enter parameters such as S_{20}, S_j, Energy per blow, number of blows per minute, bit diameter and type of bit.
  - Evaluate the value of length of cutting edge of the tool based on the type of bit used.
- Calculate the ROP by using the suitable formula.
- Print the result.
- End

```
else if (d==3){
  printf("\nBenaola, 1985 -\n\n");
  printf("Brittleness index (S20 value) of the rock: ");
  scanf("%f",&S20);
  printf("Sievex's J value (Sj): ");
  scanf("%f", &Sj);
  DRI=(1.036251*S20)+(0.142619*Sj)+1.14546;
  printf("Energy per blow (lbs.ft): ");
  scanf("%f",&Eg);
  printf("Number of blows per minute: ");
  scanf("%f",&ng);
  printf("Bit diameter (cm): ");
  scanf("%f",&Dbit);
  printf("Type of bit used for the purpose (1.Insert/2.Button/3.Bevel)? | Enter the corresponding number: ");
  scanf("%d",&bit);
  if(bit==1){
          Lf=1.7*Dbit-0.7;
      printf("\nFor the system using Insert bit, following results are obtained -\n\n");
      printf("Length of the cutting edge of the drill tool is %f cm.\n", Lf);
      printf("Drilling rate of the system is %f cm/min.", (Eg*ng)*(51*DRI+90)*pow(10,-6)/(Dbit*pow(Lf,0.5)));
  }
  else if (bit==2){
      printf("\nFor the system using Button bit, following results are obtained -\n\n");
      printf("Drilling rate of the system is %f cm/min.",pow((Eg*ng)*(51*DRI+90)*pow(10,-6)/(pow(1.15,0.5)*Dbit),0.6667));
  }
  else if (bit==3){
      printf("\nFor the system using Bevel bit, following results are obtained -\n\n");
      printf("Drilling rate of the system is %f cm/min.",pow((Eg*ng)*(51*DRI+90)*pow(10,-6)/(pow(0.85,0.5)*Dbit),0.6667));
  }
  else{
      printf("Check your input number!");
```

Figure 6: Code (Benaola, 1985)

```
Mechanical Drilling types commonly used in mines:
a - Rotary Percussive Drilling
b - Rotary Drilling

Type for which you want to find the ROP (Enter the adjacent alphabet) -
Your choice? a

Different methods for Rotary Percussive drilling:
1 - USBM, 1969
2 - Norway, 1979
3 - Benaola, 1985

Your selected method for estimating ROP (Enter the corresponding number. For example, 2 for Norway, 1979): 3

Benaola, 1985 -

Brittleness index (S20 value) of the rock: 45
Sievex's J value (Sj): 100
Energy per blow (lbs.ft): 4410
Number of blows per minute: 44
Bit diameter (cm): 4
Type of bit used for the purpose (1.Insert/2.Button/3.Bevel)? | Enter the corresponding number: 1

For the system using Insert bit, following results are obtained -

Length of the cutting edge of the drill tool is 6.100000 cm.
Drilling rate of the system is 63.911662 cm/min.
```

Figure 7: Output (Benaola, 1985)

B1. Bauer and Calder, 1967 –

Pseudo Code (Bauer and Calder, 1967)

- Start
- Let the user enter parameters such as Pull-down force, bit diameter, UCS, K-factor.
  - User enters these values in the units mentioned against each of them. However, for some of them like UCS, unit conversion has been made in the code only.
- Calculate the ROP by using the formula.
- Print the result.
- End

```
if (d==1){
printf("\nBauer and Calder, 1967 -\n\n");
printf("Pull down force (pounds): ");
scanf("%f",&Ep);
printf("Bit diameter (inches): ");
scanf("%f",&D);
printf("Uni-axial compressive strength of the rock (MPa): ");
scanf("%f",&UCS);
printf("Enter the K -factor: ");
scanf("%f",&K);
printf("Penetration rate for this condition is %f ft/hr.",
       6*pow(10,K*log(12*(Ep/D)/(UCS*145.038))/log(10)));
```

Figure 8: Code (Bauer and Calder, 1967)

```
Mechanical Drilling types commonly used in mines:
a - Rotary Percussive Drilling
b - Rotary Drilling

Type for which you want to find the ROP (Enter the adjacent alphabet) -
Your choice? b

Different methods for Rotary drilling:
1 - Bauer and Calder, 1967
2 - Bauer, 1971
3 - Calder and Workman, 1994

Your selected method for estimating ROP (Enter the corresponding number. For example, 2 for Bauer, 1971): 1

Bauer and Calder, 1967 -

Pull down force (pounds): 60000
Bit diameter (inches): 9
Uni-axial compressive strength of the rock (MPa): 90
Enter the K -factor: 1.7
Penetration rate for this condition is 130.819636 ft/hr.
```

Figure 9: Output (Bauer and Calder, 1967)

B2. Bauer, 1971 –

Pseudo Code (Bauer, 1971)

- Start
- Let the user enter parameters such as Pull-down force, bit diameter, UCS, Rotary Speed.
  - User enters these values in the units mentioned against each of them. However, for some of them like UCS, unit conversion has been made in the code itself.
- Calculate the ROP by using the formula.
- Print the result.
- End

```
else if (d==2){
printf("\nBauer, 1971 -\n\n");
printf("Pull down force (lbs): ");
scanf("%f",&Ep);
printf("Bit diameter (inches): ");
scanf("%f",&D);
printf("Uni-axial compressive strength of the rock (MPa): ");
scanf("%f",&UCS);
printf("Rotary speed of drill (rpm): ");
scanf("%f",&Nr);
printf("Penetration rate for this condition is %f ft/hr.",
       (61-28*(log(UCS*145.038/1000)/log(10)))*Ep*Nr/(D*1000*300));
```

Figure 10: Code (Bauer, 1971)

```
Mechanical Drilling types commonly used in mines:
a - Rotary Percussive Drilling
b - Rotary Drilling

Type for which you want to find the ROP (Enter the adjacent alphabet) -
Your choice? b

Different methods for Rotary drilling:
1 - Bauer and Calder, 1967
2 - Bauer, 1971
3 - Calder and Workman, 1994

Your selected method for estimating ROP (Enter the corresponding number. For example, 2 for Bauer, 1971): 2

Bauer, 1971 -

Pull down force (lbs): 70000
Bit diameter (inches): 9
Uni-axial compressive strength of the rock (MPa): 75
Rotary speed of drill (rpm): 60
Penetration rate for this condition is 49.741680 ft/hr.
```

Figure 11: Output (Bauer, 1971)

B3. Calder and Workman, 1994 –

Calder and Workman, 1994

$$ROP = 5.7 \times 10^{-5} \times (R_F - 28log_{10}(0.145\ RC))\, EN_r$$

Where, ROP is in m/hr; R_F is the penetration factor; RC is the rock uniaxial compressive strength in MPa; E is the load per unit diameter of the bit in kg/mm; N_r is the rotational speed in RPM.

Pseudo Code (Calder and Workman, 1994)

- Start
- Let the user enter parameters such as Feed force, bit diameter, UCS, rotation speed.
  - Once user enters the value of UCS, the system automatically calculates the value of rock penetration factor based on the function generated between Rf and UCS.
- Calculate the ROP by using the formula.
- Print the result.
- End

```
else if (d==3){
printf("\nCalder and Workman, 1994 -\n\n");
printf("Pull down force (Kg): ");
scanf("%f",&Ep);
printf("Bit diameter (mm): ");
scanf("%f",&D);
printf("Uni-axial compressive strength of the rock (MPa): ");
scanf("%f",&UCS);
printf("Rotary speed of drill (rpm): ");
scanf("%f",&Nr);
Rf=7714.95-7312.3*pow(UCS,0.0086436);
printf("Penetration rate for this condition is %f m/hr.",
       5.7*pow(10,-5)*(Rf-28*log(0.145*UCS)/log(10))*Ep*Nr/D );
```

Figure 12: Code (Calder and Workman, 1994)

```
Your selected method for estimating ROP (Enter the corresponding number. For example, 2 for Bauer, 1971): 3

Calder and Workman, 1994 -

Pull down force (Kg): 30000
Bit diameter (mm): 311
Uni-axial compressive strength of the rock (MPa): 200
Rotary speed of drill (rpm): 80
Penetration rate for this condition is 8.374408 m/hr.
```

Figure 13: Output (Calder and Workman, 1994)