Bearing Capacity Prediction of Mine Hauling Road Using Cone Penetration Testing (CPT)

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Abstract. Mine hauling road plays an important role in open pit mining that serves as the main link for transports to significant locations, such as connection from pit/quarry – crusher – stockpile/rom – jetty. Inadequate bearing capacity could result in construction failure of the haul road, therefore it is important to understand the bearing capacity of the sub base layer along the determined haul road route. Cone Penetration Test (CPT) was utilized to obtain the insitu geotechnical data used for determining the haul road bearing capacity. Results show that the occurrence of hard layer along the haul road route varies from the depth of 3.40 (CPT12) to 12.20 m (CPT06). Calculated bearing capacity of the sub base layer shows varying results along the road route. Minimum ultimate bearing capacity (qul) of 430.49 kN/m² is found in CPT-06 site with allowable bearing capacity (qall) of 215.24 kN/m². While maximum ultimate bearing capacity (qul) occurs in CPT-04 site of 2058.71 kN/m² with the allowable bearing capacity (qall) of 1029.35 kN/m². The calculated average ultimate bearing capacity (qul) is 1151.47 kN/m² and allowable bearing capacity (qall) 575.74 kN/m². It is suggested that the type of dump truck used for hauling should have tire pressure less than or equal to 575.74 kN/m2, in order to maintain the road during mining lifetime and prevent road deterioration.

1. Introduction

Mine hauling road is one of the most important infrastructures in an open-pit mining operation. Mine haul road serves as an inter link to several important locations, such as: pit/quarry – crusher – stockpile/rom – jetty. Errors on the planning can result in construction failures, increase of maintenance costs, and hence disrupting the mine production activities. As an important infrastructure, the plan of this road requires serious attention. An aspect that need to be considered in the design of the hauling road is prediction of the bearing capacity of the sub base layer along the determined haul road route. To obtain data, geotechnical investigation is required to compute the bearing capacity and also to characterize the sub base layers.

Cone Penetration Test (CPT) method was selected for in-situ geotechnical investigation. CPT method was chosen due to its simplicity, low cost operation, and easy mobilization. As for CPT data are

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widely used and reliable for bearing capacity and foundations. A series of investigations were carried out in a coal mining company PT.X in Loa Janan Area, Kutai Kartanegara District of East Kalimantan Province (Figure 1). Figure 1 shows that 14 cone penetration tests had been carried out along the proposed mine haul road. The length of the road was about 15 km. The results of geotechnical investigations such as CPT data which will be used to determine the layers beneath the surface and also to calculate the bearing capacity of the sub-base layer of the proposed mine hauling route. In the future, this research will also benefit to company management to decide the type of dumptruck which will be used and in designing the pavement of the hauling road.

2. Soil Investigations
CPT (Cone Penetration Test) had been conducted to obtain the data required to determine the bearing capacity of the sub-base layer for construction of hauling road route in the coal mining. CPT test works by penetrating the subsurface soil where cone resistance ($q_c$) and frictional resistance ($f_c$) are measured. Resistance to cone penetration is the resistance of soil to the cone tip, expressed in force per unit area. Frictional resistance is the shear resistance of soil against the sleeve located above the cone, expressed in force per unit length. The $q_c$ and $f_c$ values are capable to indicate strength of the in-situ soil. Results of CPT test are depicted in the graphs which state the inter relation of the depth of soil layer and the magnitude of the cone penetration resistance ($q_c$) (ASTM D 3441-10; SNI 03-2827-2008). From this in situ test, several parameters of soil resistance consist of cone resistance ($q_c$), shear resistance ($f_c$), friction ratio ($F_r$), and total resistance ($T_f$) were obtained.
2.1 Determination of Soil Parameters Based On CPT Data

The field investigation of CPT test is usually used as preliminary investigation. For cases where the geotechnical logging or soil properties are difficult to obtained, a result from field investigation can be considered. Determination of soil parameters was usually done based on engineering judgement and correlation of soil properties based on field investigation data such as CPT. Methods to determine these parameters relate to soil classification and it's shear strength are shown in Figure 2 – Figure 5 below.

![Figure 2. Soil classification based on CPT data (Robertson & Campanella, 1983)](image)

![Figure 3. Correlation of soil properties based on CPT data (Robertson & Campanella, 1983).](image)
2.1.1. Cohesive soil (clay). Sanglerat (1972) showed that shear strength of clay of undrained condition ($c_u$) can be determined based on cone resistance. The relationship of undrained shear strength of clay and cone resistance was shown in the formula below.

$$c_u = \frac{q_c}{15} s / d \frac{q_c}{20}$$

The formula being used in this paper was:

$$c_u = \frac{q_c}{15}$$

| Consistency     | Undrained Cohesion (ton/m$^3$) |
|-----------------|---------------------------------|
| Very soft       | less than 1.25                  |
| Soft            | 1.02 – 2.50                     |
| Medium stiff    | 2.50 – 5.00                     |
| Stiff           | 5.00 – 10.00                    |
| Very stiff      | 10.00 – 20.00                   |
| Hard            | over 20.00                      |

*Figure 4. Correlation of Young’s Modulus (undrained) with Plasticity Index of clay (Sanglerat, 1972).*
2.1.2 Non-cohesive soil (sand). Robertson & Campanella (1983) show that the friction angle (ϕ) of sand can be determined based on the value of q_c and σ_v0. Figure 5 show the relationship between the values of q_c, σ_v0, and ϕ' for sand.

![Cone bearing q_c, MPa](image)

**Figure 5.** Correlation of q_c, σ_v0, and ϕ' of sand (Robertson & Campanella, 1983).

Parameter values of soil stiffness and deformation relate to the type of soil are shown in Table 2 below.

| Type of soils      | Modulus of Elasticity | Poisson’s ratio |
|--------------------|-----------------------|-----------------|
|                    | (MN/m²) | (lb/in²) | µs   |
| Loose sand         | 10.5 – 24.0 | 1500 – 3500 | 0.20 – 0.40 |
| Medium dense sand  | 17.25 – 27.60 | 2500 – 4000 | 0.25 – 0.40 |
| Dense sand         | 34.50 – 55.20 | 5000 – 8000 | 0.30 – 0.45 |
| Silty sand         | 10.35 – 17.25 | 1500 – 2500 | 0.20 – 0.40 |
| Sand and gravel    | 69.00 – 172.50 | 10000 - 25000 | 0.15 – 0.35 |
| Soft clay          | 4.1 – 20.7   | 600 – 3000  |     |
| Medium clay        | 20.7 – 41.4  | 3000 – 6000 | 0.20 – 0.50 |
| Stiff clay         | 41.4 – 96.6  | 6000 - 14000 |     |
3. Bearing Capacity of Soil

Bearing capacity of soil is the ability of soil to support the structures upon it without experiencing failures. This capacity needs to be analyzed so that the sub-base layer does not experience shear failure and excessive settlement. It is determined by the type and characteristic of soil, and is also influenced by the shear strength of soil that comprises of cohesion and friction angle. If the shear stress acting on a soil mass then simultaneously the normal stress (σ) will work, then the shear stress (τ) will increase when deformation reaches the limit. If the limit values are connected with different normal stresses (σ), then a straight line will be obtained where cohesion as a constant and normal stress (σ) as a variable, and the slope of the line is determined as the friction angle. Then, it can be written in the equation as follows:

\[ \tau = c + \sigma \tan \phi \]

in which: \( \tau \) = shear stress of soil (kg/cm²)  
\( c \) = cohesion (kg/cm²)  
\( \sigma \) = normal stress (kg/cm²)  
\( \phi \) = angle of friction (°)

From the equation above, cohesion (c) is obtained from the magnitude of cohesive between soil grains while resistance to soil particles termed as friction angle (ϕ). Both parameters can be determined from soil laboratory testings or empirically based on CPT data.

For designing of hauling road, the bearing capacity formula on shallow foundation was chosen for analysis. Based on British Standard (2004), shallow foundation has a depth of influence of less than 2 meters below the surface. Some examples consist of spread foundation and raft foundation. Terzaghi, in Das and Sobhan (2018), introduced the formula of bearing capacity of soil which is calculated as the ultimate bearing capacity (q_{ult}), that is an ultimate condition of the capacity itself. If it is exceeded, it will cause failure of soil. Therefore, the value of the allowable bearing capacity (q_{a}) must be less than the value of the ultimate bearing capacity (q_{ult}). Allowable bearing capacity (q_{a}) depends on the selected safety factor (F). Commonly, the value of safety factor is about 2 to 5, and the value of the allowable bearing capacity is calculated with the formula below.

\[ q_a = \frac{q_{ult}}{F} \]

in which: \( q_a \) = allowable bearing capacity (kN/m²)  
\( q_{ult} \) = ultimate bearing capacity (kN/m²)  
\( F \) = safety factor

Furthermore, the calculation of the ultimate bearing capacity (q_{ult}) refers to the general equation of the bearing capacity of soil below.

\[ q_{ult} = cN_c + \gamma D_f N_q + 0.5\gamma B N_y \]

in which: \( q_{ult} \) = ultimate bearing capacity (kN/m²)  
\( c \) = cohesion of soil (kN/m²)  
\( q = \gamma \times D_f \) (density × depth)  
\( \phi = \) internal friction angle (°)  
\( N_c, N_q, N_y \) = bearing capacity factors (Figure 6)
Terzaghi also develop a formula for the influence of shape factor of foundation on the general equation of ultimate bearing capacity ($q_{ult}$) and categorized into two group:

1. Square footing, refers to the formula below

$$q_{ult} = 1.3cN_c + \gamma D_q N_q + 0.4 \gamma BN_f$$

2. Circular footing, refers to the formula below

$$q_{ult} = 1.3cN_c + \gamma D_q N_q + 0.3 \gamma BN_f$$

4. Results and Discussion

This investigations was carried out before the construction stage. It was a model calculation to give insights about the condition of subsurface and the bearing capacity of soil layers. The results of the CPT testing on location of CPT-01 to CPT-14 can be seen on in Table 3. as follows:

| Test No. | Depth (m) | Cone Resistance (kg/cm2) | Total Resistance (kg/cm2) |
|----------|-----------|--------------------------|---------------------------|
| CPT-01   | 6.40      | 250                      | 380                       |
| CPT-02   | 4.00      | 300                      | 400                       |
| CPT-03   | 5.40      | 280                      | 390                       |
| CPT-04   | 5.40      | 145                      | 280                       |
| CPT-05   | 8.60      | 220                      | 350                       |
| CPT-06   | 12.20     | 210                      | 300                       |
| CPT-07   | 6.40      | 150                      | 260                       |
| CPT-08   | 5.20      | 190                      | 280                       |
| CPT-09   | 11.20     | 180                      | 305                       |
| CPT-10   | 6.80      | 150                      | 285                       |
| CPT-11   | 3.60      | 310                      | 380                       |
| CPT-12   | 3.40      | 280                      | 400                       |
| CPT-13   | 4.00      | 180                      | 260                       |
| CPT-14   | 8.00      | 220                      | 320                       |

Figure 6. Values of bearing capacity factors (Terzaghi, 1996).
The interpretation of CPT testing show that the lithology of the subsurface consists of clay, sand, silty sand, sandy silt, and silty clay. The lithology of the subsurface on CPT-01 can be seen on Figure 7 as follows.

![Figure 7. Lithology of CPT-01 Log](image)

The bearing capacity of sub-base layer in each CPT testing location is calculated by assuming that the load which will work comes from dump trucks passing through the hauling road. Because of the load of dump truck only work at the surface, the analysis on the shallow foundation was used. Load on each wheel was assumed as a circular foundation so that the analysis of the ultimate bearing capacity was carried out by using the Terzaghi equation for the circular foundation. Furthermore, the Terzaghi equation is based on the case of shallow foundation where the foundation is constructed beneath the surface. In the case of dump truck, the wheels of truck only work at the road surface and the load is distributed through pavement layers designed to burden the traffic load from the dump trucks. So, the depth of foundation ($D_f$) was zero where $B = d = 0.96$ m, that is the diameter of the wheel and the load acting on the surface with soil density $\gamma = 20$ kN/m$^3$.

Bowles (1991) offers a recommendation that a safety factor of 2.0 for cohesionless soil and 3.0 for cohesive soil can be used. The type of material used for road construction at the surface usually cohesionless soil or has a low cohesion value so the safety factor, $F = 2.0$, will be used to calculate the allowable bearing capacity ($q_a$), which is the tire pressure of the dump truck. In CPT testing, soil that is assumed to be cohesive (clay) have zero friction angle and soil that is assumed to be cohesionless (sand) only has friction angle. Based on Figure 5, the $N_c$ factor for cohesive soil is 5.7 and cohesion is then calculated using the value of cone resistance ($q_c$). While for cohesionless soil (sand), friction angle is determined by using Figure 4. The calculation results of the bearing capacity at each CPT testing location is summarised in Table 4 below.
Table 4 Results of bearing capacity calculation at each location.

| Test No. | Location  | Ultimate Bearing Capacity (kN/m²) | Allowable Bearing Capacity (kN/m²) |
|----------|-----------|-----------------------------------|-----------------------------------|
| CPT-01   | Stockpile | 1471.05                           | 735.53                           |
| CPT-02   | Stockpile | 1143.50                           | 571.75                           |
| CPT-03   | Haul road | 987.28                            | 493.64                           |
| CPT-04   | Haul road | 2058.71                           | 1029.35                          |
| CPT-05   | Haul road | 748.46                            | 374.23                           |
| CPT-06   | Haul road | 430.49                            | 215.24                           |
| CPT-07   | Haul road | 1336.71                           | 668.35                           |
| CPT-08   | Haul road | 883.67                            | 441.83                           |
| CPT-09   | Stockrom  | 951.67                            | 475.83                           |
| CPT-10   | Stockrom  | 1173.69                           | 586.84                           |
| CPT-11   | Hill      | 1898.33                           | 949.16                           |
| CPT-12   | Valley    | 854.50                            | 427.25                           |
| CPT-13   | Right side haul | 1680.76 | 840.38                           |
| CPT-14   | Left side haul | 501.82 | 250.91                           |
| Average  |           | **1151.47**                       | **575.74**                       |
| Max      |           | 2058.71                           | 1029.35                          |
| Min      |           | 430.49                            | 215.24                           |

From Table 4.2 above, the average of allowable bearing capacity ($q_a$) of sub-base layer is 575.74 kN/m². The selection of the type of dump truck will be based on this value in which the tyre pressure should be equal to or less than 575.74 kN/m². This pressure must be maintained daily during mine operation so that the hauling road will not be easily deteriorated and able to serve during the mining lifetime. In addition, pavement design of the hauling road must also be well designed in order to increase the rolling resistance, the bearing capacity of the surface and base course layer. On the other hand, it was better to put some devices in monitoring point when the construction being made in order to validate the model results in the field.

Conclusions

The results of CPT testing represent a variety of depth of hard layer in each testing location, begin with a minimum depth of 3.4 meters at the CPT-12 location on the valley area up to a maximum depth of 12.20 meters at the CPT-06 location on the hauling road.

Calculation of the bearing capacity of soil also indicate a variety of results. The minimum value of the ultimate bearing capacity ($q_{ult}$) is 430.49 kN/m² and of the allowable bearing capacity ($q_a$) is 215.24 kN/m² which is located at the CPT-06 location on the area of the hauling road, while the maximum value of the ultimate bearing capacity ($q_{ult}$) is 2058.71 kN/m² and of the allowable bearing capacity ($q_a$) is 1029.35 kN/m² at the CPT-04 location on the hauling road.

The average value of the calculation results as follow: the ultimate bearing capacity ($q_{ult}$) is 1151.47 kN/m² and the allowable bearing capacity ($q_a$) is 575.74 kN/m². The selection of the type of dump truck will be based on this value in which the tire pressure will equal or less than 575.74 kN/m². This
pressure must be maintained daily in mine operation so that the hauling road become not easily deteriorated and serve during the mining lifetime.

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