Evaluation of Ground Bearing Capacity Estimation Methods Based On Plate Loading Tests

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Abstract. Within the scope of this study, bearing capacities were calculated based on eleven different estimation methods in literature, using some mass and material properties for different rock units (magnetite, syenite, serpentinite, limestone, clayey limestone and gypsum) encountered in three different open-pit mines (Sivas-Ulaş Open-Pit Celestite Mine, Divriği Open-Pit Iron Mine and Kangal Open-Pit Coal Mine) around Sivas in Turkey. Through regression analyses between estimated bearing capacity values and those that had been determined as a result of plate loading tests, bearing capacity estimation methods specified in the literature were assessed. Moreover, four different equations to be used in bearing capacity estimation were proposed.

1. Introduction
Safe, economical, and efficient digging-loading and haulage operations in open-pits are only possible through selection of optimum equipment and design of convenient operation areas and roads. One of important parameters taken into account in design works of excavation areas and mine roads is the ground bearing capacity. Determination of bearing capacity sets forth whether existing or prospective digging-loading machines, which are excavators, draglines, loaders, etc., would have problems of settlement in the ground, and whether existing or prospective transportation vehicles would be able to operate on roads constructed and/or to be constructed. Ground bearing capacity is a determining factor in selecting or eliminating some excavators. After determining the bucket capacity, the excavator is examined for the pressure it applies to the ground. If the ground bearing capacity is higher than the pressure applied by an excavator but the floor condition is poor, then a smaller excavator should be selected. In this study, bearing capacity values defined in eight different units in three different open-pits (Sivas-Ulaş Open-Pit Celestite Mine, Divriği Open-Pit Iron Mine and Kangal Open-Pit Coal Mine) are used and estimation methods in literature are assessed.

2. Estimation methods of bearing capacity
When a load is applied on the surface of any substance, it initially leads to elastic, and then permanent deformations on such substance. Likewise, when a load is applied to grounds, they are somewhat compressed and become consolidated depending on their characteristics and the applied load. As such spaces do not fail unless shear stresses occur on soil grounds or rock units, they can act elastically. After a certain level of stress, however, irreversible deformations take place on soil grounds and rock units. Concept of bearing capacity, which refers to the fact that a ground is sufficiently safe against failure, is very important. Failure of foundations leads to collapse of superstructure as well. In order for a superstructure to fulfill required function, total and separate subsidence on the ground of foundations
must not exceed acceptable values. Bearing capacity (q_u), transferred stress of foundation structure without failure is expressed with maximum ground pressure (kg/cm² or t/m²). The load used in determination of bearing capacity is known as the maximum load the ground can bear right before failure thereof. Bearing capacity obtained upon determination of ground bearing capacity by any method is divided by safety factor (SF) (q_a = q_u / SF) so that allowable ground stress is obtained. Safety factor values used in geotechnical engineering typically ranges between 2.5 and 3.5. Mylivec (1978) indicates that this value rarely decreases to 2.0 and rises to 4.0 [1]. Upon obtaining allowable ground stress, it is ensured that ground stresses are not above this value when foundations are designed. In determining safety factor used in defining allowable ground stresses, the points such as; ground type, type of superstructure, superstructure load and life, instability of the ground, data obtained from field survey and laboratory tests are taken into consideration. A foundation under a sufficiently big amount of load may settle and slump in the ground with an increasing speed. Many surveys have been made to determine the size of load that leads to such a failure. In such surveys, both physical characteristics of the ground were analyzed and ground motion under load was considered. A number of theories and methods were developed related with this subject. However, only little number of them coincided with the results of tests conducted according to experiences and one-to-one scale. Bearing capacity is based on mechanical characteristics of the ground such as unit weight, shear strength and deformation characteristics; ground’s initial state of stress; discontinuity properties; geometric and physical conditions of the ground such as size, depth, shape, base roughness and load it bears; and method of construction. It is possible to review estimation methods of bearing capacity under two main topics as analytical, empirical and experimental methods. Numerous researchers have established many equations regarding determination of ground bearing capacity with analytical and empirical methods [2-16]. In analytical solutions, parameters of ground shear strength (cohesion “c” and angle of internal friction “ϕ”) are deemed to be known.

As known, structural elements found in rock mass but not found in rock sample affect results of load bearing capacity. Thus, bearing capacities of foundations are more properly determined through in situ tests. Through such in situ tests, disturbing in sampling is minimized, and the ground is subjected to tests under existing environmental conditions (stress distribution, pore pressure, degree of saturation). Although there are several field tests, only some of them are more frequently used than the rest [17]. Tests used for in situ determination of bearing capacity are standard penetration test, cone penetration test, vane shear test, pressure meter test, plate loading test.

Plate loading test is particularly able to determine bearing capacities of foundations or ground layers of transportation structures such as flat foundations of road and runway constructions. Figure 1 shows the modes of failure of a footing on rock. If foundation exhibits a heterogeneous structure, failure is accelerated and load distribution is affected, which leads load counters under the foundation to differentiate.

V-shape wedge that emerges under the foundation in soil grounds stiffens and leads side sections to be pushed. Thus, elevations on grounds on the side sections of plate are seen when pushing starts while ground platen was moving longitudinally during stiffening. Strength in rock units is more than that in soil; however, this material has a strength limit, too, and when such limit is reached, the rock is defeated and cracked. At this stage, load bearing capacity decreases rapidly but resistance against axial load does not fall immediately but is reduced gradually in time as is in triaxial compressive strength test because of horizontal stresses exerted by the side rocks. Rocks behave as soil grounds, after the rock underground platen is completely cracked (Fig. 1).
3. Evaluation of bearing capacity estimation methods

Rock units are generally assumed to be very good foundation units. However, overload leads to considerable subsidence or sudden failures in rock masses, too. Therefore, as in design of the foundation on the ground, much attention and care should be paid to the design of foundation to be constructed on rock masses. In calculations during foundation designs, rock masses are usually grouped under two main classes such as weathered and fresh, and some mechanical properties of the rock unit are taken into consideration.

This study aims at assessing rock units, bearing capacities of which were determined by plate loading test in the field, according to estimation methods of bearing capacity in the literature. Literature includes various empirical methods for estimation of bearing capacities of rock units. Among these methods, were those having field and laboratory surveys as their parameters assessed. Equations from which bearing capacities of the units worked on can be estimated are given in Table 1 in detail.

3.1. Bearing capacities and some important properties of studied units

In this study, bearing capacities of different rock units (magnetite, syenite, serpentinite, limestone, clayey limestone and gypsum) found in Sivas-Ulaş Open-Pit Celestite Mine, Divriği Open-Pit Iron Mine and Kangal Open-Pit Coal Mine around Sivas, and of operation areas (soil, dumping area) were calculated using empirical formulas of the literature (Table 1), and compared with bearing capacity values obtained as a result of in situ plate loading tests. Results of field observations and measurements conducted for determination of mass properties of the units in question and bearing capacity values of these units are shown in Table 2, and Table 3 presents the laboratory test results.

3.2. Evaluation of estimation methods

This section includes bearing capacity estimations done by using some empirical formulas in the literature with respect to different rock units (magnetite, syenite, serpentinite, limestone, clayey limestone and gypsum) found in three open-pit mines around Sivas (Tables 4 and 5).

With the purpose of comparing estimated and measured bearing capacity values, simple regression analyses (linear, exponential, and logarithmic function approaches) were made. As a result of such regression analyses, relations with acceptable correlation (r = 0.64 - 0.82) between measured and estimated bearing capacities were obtained (Table 6). As shown in Table 5, estimated bearing capacity values greatly differed from others with respect to in situ determined bearing capacity values in most of the equations. For example, bearing capacity value of magnetite, obtained as a result of plate loading test is 110.49 kg/cm² while the closest value to this during calculations was that of El-Naqa (Equation K) (91.08 kg/cm²). In syenite unit, the closest result to measured bearing capacity value was obtained from equation J. Similar situations apply for other units, too.
| Equation Code | Equation | Proposed By |
|---------------|----------|-------------|
| Equation A    | $q_u = 1 + \frac{RQD/16}{(1 - \frac{RQD}{130})}$ | Peck et al. [2] |
| Equation B    | $q_u = 10.0V_p^3$ | Imai and Yoshimura [3] |
|               | $q_u = s^{0.5} * q_{un} * (1 + (mS - 0.5 + 1)^0.5)$ | |
| Equation C    | $s = \exp\left(\frac{RMR - 100}{9}\right)$ | Wyllie [5] |
|               | $m = m_i \exp\left(\frac{RMR - 100}{28}\right)$ | |
| Equation D    | $q_u = q_{un} * \left[s^{0.5} + (mS - 0.5 + s)^0.5\right]$ | Bell [4] |
| Equation E    | $q_u = 3 * (0.0364 * RMR^{1.6168})$ | Mehrotra, 1992: from Singh and Goel [10] |
|               | $q_u \approx Jq_{un}$ | |
| Equation F    | $E_m = \frac{E_i}{100} * [0.0028(RMR)^2 + 0.9e^{0.19716}]$ | Mehrotra, 1992: from Singh and Rao [14] |
|               | $q_u = 2c_{mass} * \tan(45 + \phi/2)$ | |
| Equation G    | $c_{mass} = \frac{q_{un} * s}{2 \tan(45 + \phi/2)}$ | Anonymous [21] |
|               | $s = \exp\left(\frac{RMR - 100}{9}\right)$ | |
| Equation H    | $q_u = \frac{dV_p^2}{100}$ | Keçeli [6] |
| Equation I    | $q_u = q_{un} (q_f / q_{un})$ | Bowles [8] |
| Equation J    | $q_u = K_vq_{un}$ | Anonymous: from Şekercioğlu [11] |
| Equation K    | $q_u = 0.0483e^{0.0725 GSI} * 10.19716$ | El-Naqa [13] |

* $q_u$ - Ultimate bearing capacity, kg/cm²; RQD - Rock quality designation, %; $V_p$ - Seismic velocity (P-Wave), km/s; $q_{un}$ - Uniaxial compressive strength, kg/cm²; $m$ - Rock mass Hoek–Brown’s constants; $m_i$ - Intact rock Hoek–Brown’s constant; RMR - Rock mass rating; $S$ - Discontinuity spacing, cm; $J$ - Mass factor; $E$ - Intact rock deformation modulus, GPa; $E_m$ - Rock mass deformation modulus, [GPa]; $c_{mass}$ - Rock mass cohesion, [kg/cm²]; $\phi$ - Internal friction angle [°]; $d$ - Natural unit weight, gr/cm³; $V_p$ - Seismic velocity (P-Wave), [m/s]; $q_f / q_{un}$ - Correction factor; $K_v$ - Empirical constant depends on discontinuity spacing; $GSI$ - Geological strength index.
When relations obtained as a result of regression analyses between measured and estimated bearing capacities (Table 6) were examined (Equation A, $r = 0.81$; Equation B, $r = 0.82$; Equation H, $r = 0.75$; Equation I, $r = 0.64$), relations with acceptable correlation coefficients were obtained from approaches where RQD and seismic velocity are taken into account. Nevertheless, results obtained from equation A [2] and equation H [6] were seen to be less than measured bearing capacities. Those obtained from equation B [3] were much below measured values although a relation with a high correlation coefficient was established. Moreover, results received from Equation 1 [8] are much above the measured bearing capacity values. As expected, bearing capacity values estimated from equations reflecting rock mass properties best and containing particularly the effect of discontinuities in rocks are closer to measured values.

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**Table 2. Results of geotechnical observations and in situ tests [23]**

| Location         | Studied Unit | Geotechnical Description | Bearing capacity (kg/cm²) | Seismic velocity P-wave (m/s) | RMR (description, class) | Ease of Digging/Ripping (weighted class, description) | RQD |
|------------------|--------------|----------------------------|---------------------------|-------------------------------|--------------------------|------------------------------------------------------|-----|
| Sivas - Divriği | Magnetite    | Dark grey, slightly weathered. Joint set No: 3 Average joint spacing 3.0 m Stepped - smooth. Grey, fresh. | 110.5                     | 651                           | 77 (Good Rock, II)       | 4 (Difficult)                                        | 93  |
| Iron Mine        | Syenite      | Grey, fresh. Joint set No: 2 Average joint spacing 0.4 m Planar - smooth. Greenly grey, slightly weathered. | 115.9                     | 752                           | 64 (Good Rock, II)       | 3 Moderately Difficult                               | 78  |
| Serpentine       | Limestone    | Joint set No: 2 Average joint spacing 2.0 m Stepped - smooth. Light grey-brownish, slightly weathered. | 97.7                      | 718                           | 72 (Good Rock, II)       | 3 Moderately Difficult                               | 92  |
| Sivas - Kangal  | Clayey limestone | Average joint spacing 1.5 m Undulating – rough. Cream to light brownish, moderately weathered. | 148.5                     | 1006                          | 64 (Good Rock, II)       | 3 Moderately Difficult                               | 92  |
| Coal Mine        |              | Average joint spacing: 0.8 m Undulating – rough. | 119.5                     | 814                           | 49 (Fair III)            | 3 Moderately Difficult                               | 84  |
| Dumping area a   |              | Light gray, slightly weathered. Joint set No: 2 Average joint spacing 4.4 m Undulating – smooth | -                         | 130.7                         | -                        | -                                                    | -   |
| Sivas - Gypsum  | Soil         | Brown, completely weathered | 34.9                      | 450                           | -                        | 1 Easy                                               | -   |
| Ulaş Celestite   |              |                            |                           |                               |                          |                                                      |      |
| Mine             |              |                            |                           |                               |                          |                                                      |      |

*a Composed of limestone and clayey limestone spoil pile turned into road bed.*
**Table 3. Laboratory test results [23]**

| Property                        | Rock Unit                    |
|---------------------------------|------------------------------|
|                                 | Magnetite | Syenite | Serpentinite | Limestone | Clayey limestone | Gypsum |
| Grain unit weight (gr/cm³)      | 4.77      | 2.70    | 2.92         | 2.67      | 2.63             | 2.96   |
| Natural unit weight (gr/cm³)    | 4.67      | 2.67    | 2.87         | 2.42      | 2.38             | 2.30   |
| (4.55-4.82)                     | (2.65-2.69)| (2.80-2.93)| (2.32-2.50) | (2.24-2.44) | (2.23-2.36)     |
| Dry unit Weight (gr/cm³)        | 4.66      | 2.65    | 2.86         | 2.35      | 2.29             | 2.00   |
| Total porosity (%)              | 2.22      | 2.33    | 2.15         | 11.95     | 13.04            | 32.43  |
| Moisture cont. (%)              | 0.14      | 0.17    | 0.22         | 1.22      | 3.78             | 14.26  |
| Indirect tensile strength (MPa) | 6.8       | 9.2     | 6.0          | 3.1       | 2.4              | 2.4    |
| (4.8-9.5)                       | (6.3-13.0)| (5.2-8.2)| (2.9-3.3)   | (1.6-3.2) | (1.3-3.0)        |
| Uniaxial compressive strength (MPa) | 77.1   | 112.5   | 52.1         | 34.1      | 17.3             | 14.6   |
| (68.2-87.0)                     | (91.1-147.6)| (39.8-65.9)| (16.8-58.0)| (9.0-28.5) | (9.0-22.5)       |
| Cohesion (MPa)                  | 25.8      | 17.8    | 16.5         | 7.4       | 3.7              | 4.0    |
| Internal friction angle (°)     | 22.4      | 54.8    | 25.2         | 43.2      | 44.0             | 32.8   |
| Shore hardness                  | 84.8      | 105.0   | 50.0         | 66.4      | 46.0             | 27.5   |
| Elastic modulus (Et, GPa)       | 53.5      | 58.7    | 38.3         | 36.0      | 30.2             | 23.0   |
| Poisson’s ratio (νs)            | 0.38      | 0.44    | 0.26         | 0.23      | 0.18             | 0.18   |

**Table 4. Parameters used in the equations of literature**

| Parameters                        | Rock Unit                   |
|-----------------------------------|-----------------------------|
|                                   | Magnetite | Syenite | Serpentinite | Limestone | Clayey limestone | Gypsum |
| RQD, Rock quality designation (%) | 93        | 78      | 92           | 92        | 84               | 48     |
| Vp, Seismic velocity (m/s)        | 651       | 751.5   | 718.5        | 1006.5    | 814.5            | 1826   |
| q_un, Uniaxial compressive strength (kg/cm²) | 786.19 | 1146.87 | 530.93       | 347.36    | 176.64           | 149.33 |
| RMR, Rock Mass Rating             | 77        | 64      | 72           | 64        | 49               | 59     |
| s, Rock mass constant (Equation C and D) | 0.0776 | 0.0183  | 0.0446       | 0.0183    | 0.0035           | 0.0105 |
| m, Intact rock constant           | 6.000     | 6.639   | 6.709        | 6.807     | 6.786            | 6.683  |
| m, Rock mass constant (Equation C and D) | 2.639  | 1.835   | 2.468        | 1.882     | 1.098            | 1.545  |
| S, Discontinuity spacing (m)      | 0.6       | 0.2     | 0.5          | 0.5       | 0.3              | 4.4    |
| E_t, Intact rock deformation modulus (GPa) | 53.495 | 58.715  | 38.283       | 36.002    | 30.195           | 23.035 |
| E_m, Rock mass deformation modulus (GPa) (Equation F) | 22.940 | 15.464  | 13.639       | 9.482     | 4.356            | 4.996  |
| J, Mass factor (Equation F)       | 0.429     | 0.263   | 0.356        | 0.263     | 0.144            | 0.217  |
| φ_i, Internal friction angle (°)  | 22.4      | 54.8    | 25.2         | 43.2      | 44               | 32.8   |
Table 4. Parameters used in the equations of literature (Continue).

| Parameter                      | Value  |
|--------------------------------|--------|
| $C_{mass}$, Rock mass cohesion (kg/cm²) | 20.431, 3.332, 7.504, 1.376, 0.130, 0.428 |
| $d$, Natural unit weight (gr/cm³) | 4.674, 2.671, 2.867, 2.421, 2.382, 2.3 |
| $q_{f}/q_{un}$, Correction factor | 0.79, 0.38, 0.76, 0.76, 0.54, 0.20 |
| $K_s$, Empirical constant | 0.1, 0.1, 0.1, 0.1, 0.1, 0.4 |
| $GSI$, Geological strength index (Equation K) | 72, 59, 67, 59, 44, 54 |

*Hoek et. al. [7], *b* Bowles [8], *c* Anonymous: From Şekercioğlu [11]

Table 5. Estimation of bearing capacity values of all units using empirical methods

| Bearing Capacity, $q_u$ (kg/cm²) | Studied Units | Measured | Equation A | Equation B | Equation C | Equation D | Equation E | Equation F | Equation G | Equation H | Equation I | Equation J | Equation K |
|----------------------------------|---------------|----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Measured                        | Magnetite     | 110.49   | 115.92     | 97.71      | 148.46     | 119.48     | 63.01      | 34.89      | 130.71     |
| Equation A                      | Syenite       | 64.267   | 39.563     | 62.013     | 62.013     | 47.511     | 17.268     | -          | -          |
| Equation B                      | Serpentinite  | 2.759    | 4.244      | 3.709      | 10.196     | 5.403      | 60.884     | 0.911      | 6.098      |
| Equation C                      | Limestone     | 927.944  | 747.511    | 511.329    | 228.497    | 56.463     | 76.685     | -          | -          |
| Equation D                      | Clayey limestone | 769.765 | 643.589    | 436.807    | 206.049    | 55.748     | 92.701     | -          | -          |
| Equation E                      | Gypsum        | 122.55   | 90.88      | 109.94     | 90.88      | 59.01      | 79.68      | -          | -          |
| Equation F                      | Soil          | 337.141  | 302.047    | 189.147    | 91.483     | 25.485     | 32.388     | -          | -          |
| Equation G                      | Dumping area  | 61.047   | 21.006     | 23.654     | 6.362      | 0.611      | 1.569      | -          | -          |
| Equation H                      |               | 30.428   | 20.073     | 20.599     | 24.367     | 19.401     | 41.998     | -          | -          |
| Equation I                      |               | 621.090  | 435.811    | 403.507    | 263.994    | 95.386     | 29.866     | -          | -          |
| Equation J                      |               | 78.619   | 114.687    | 53.093     | 34.736     | 17.664     | 59.732     | -          | -          |
| Equation K                      |               | 91.084   | 35.491     | 63.389     | 35.491     | 11.963     | 24.7       | -          | -          |

Table 6. Relationships between measured bearing capacity and estimated bearing capacity using the equations of literature

| Independent variable, X (Used equation) | Measured bearing capacity, $Y$ (kg/cm²) | $r$ |
|-----------------------------------------|------------------------------------------|-----|
| Equation A                              | $Y = 18.085X^{0.4646}$                    | 0.81 |
| Equation B                              | $Y = 123.02e^{0.0104X}$                   | 0.82 |
| Equation C                              | $Y = 202.17e^{0.0248X}$                   | 0.75 |
| Equation D                              | $Y = 45.154X^{0.1594}$                    | 0.64 |

3.3. Proposed equations

Firstly, an evaluation based on parameters used on eleven of bearing capacity estimation methods in the literature was made. Frequency of using such parameters in these methods was determined and their average predominance was calculated considering estimation methods they were included with the purpose of defining effectiveness of such parameters in determination of bearing capacity (Table 7). As a result of this evaluation, uniaxial compressive strength came first as the most frequently used and most effective one with a preference frequency of 5, and a predominance of 18.94%; and was followed by seismic velocity with a frequency of 2 and a predominance of 18.18%, after which RMR came with a frequency of 1 and predominance of 9.09%.
Table 7. Frequencies of parameters used in the estimation methods

| No | Parameters used in the equations | Frequencya | Weightedb (%) |
|----|---------------------------------|------------|--------------|
| 1  | \( q_{un} \), Uniaxial compressive strength (kg/cm²) | 5          | 18.94        |
| 2  | \( V_p \), Seismic velocity (m/s) | 2          | 18.18        |
| 3  | RMR, Rock Mass Rating | 1          | 9.09         |
| 4  | RQD, Rock quality designation (%) | 1          | 9.09         |
| 5  | \( m \), Rock mass constant | 2          | 5.30         |
| 6  | \( s \), Rock mass constant | 2          | 5.30         |
| 7  | \( \phi \), Internal friction angle (°) | 1          | 4.55         |
| 8  | \( K_s \), Empirical constant | 1          | 4.55         |
| 9  | \( J \), Mass factor | 1          | 4.55         |
| 10 | \( C_{max} \), Rock mass cohesion (kg/cm²) | 1          | 4.55         |
| 11 | \( q_f / q_{un} \), Correction factor | 1          | 4.55         |
| 12 | \( S \), Discontinuity spacing (m) | 1          | 2.27         |

*a Made considering the 11 estimation methods of literature.

b \( a_i \) : # of parameters in the equation, \( a_i \geq 1 \)

e : # of equation

\[
\text{Weighted} = \frac{\sum_{i=1}^{n} 100 / a_i}{e*100} * 100
\]

In light of this information, simple and multiple regression analyses were conducted considering measured bearing capacity values and results of rock mechanics in situ and laboratory tests (Table 2 and 3), and parameters used in bearing capacity estimation methods for rock units in the literature (Table 4) in order to establish equations that could be used in bearing capacity estimation.

Firstly, one-to-one simple regression (linear, exponential, and logarithmic function approaches) analyses were made using Microsoft Excel. As a result of these regression analyses, meaningful relations with high correlation (\( r = 0.65 - 0.96 \)) were provided between measured bearing capacity and total porosity, Shore hardness, correction factor (\( q_f / q_{un} \)), moisture content, rock quality designation (RQD), and seismic velocity (Table 8). As expected, the most meaningful and highest correlation (\( r = 0.96 \)) relation resulting from these simple regression analyses were established between bearing capacity and seismic velocity (Fig. 2).

Table 8. Relationships between bearing capacity and some mass/material properties

| Independent Variable, X | Bearing Capacity, \( Y \) (kg/cm²) | \( r \) |
|-------------------------|---------------------------------|-------|
| Total porosity (%)      | \( Y = 125.28 e^{-0.0159B} \) | 0.65  |
| Shore hardness          | \( Y = 18.906 (E)^{0.4243} \)   | 0.70  |
| Correction factor (\( q_f / q_{un} \)) | \( Y = 137.71(I)^{0.3983} \) | 0.75  |
| Moisture content (%)    | \( Y = 121.56 e^{-0.0423A} \)   | 0.81  |
| Rock quality designation (RQD) (%) | \( Y = 1.6124(J)^{0.9568} \) | 0.85  |
| Seismic velocity (m/sn) | \( Y = 137.52 * \ln(V_p) - 798.35 \) | 0.96  |
As shown in Figure 2, gypsum rock unit found in Sivas-Ulaş Open-Pit Celestite Mine was excluded from the regression analysis because its seismic velocity was relatively quite high (Table 2) and this affected the relation negatively. Gypsum rock unit has a quite high seismic velocity while its bearing capacity is low. It can be claimed that this is the result of fine-grained and ductile composition of gypsum rock unit, and of the fact that its discontinuity spacing (4.4 m in average) is higher and more massive than the other units.

For enhancing and developing seismic velocity - bearing capacity relation provided as a result of simple regression analysis multiple regression analyses were performed. SPSS V13.0 (Statistical analysis) package program was used in regression analyses. In all of such analyses, seismic velocity was chosen as constant independent variable both because it is more commonly used in the literature (Table 7) and it was regarded to represent and characterize rock mass properties better. Then, results of rock mechanics in situ and laboratory tests and other parameters used in the literature for bearing capacity estimation were added to the analysis respectively as independent variables. By adding independent variables to the analysis respectively, which were contained in the relation in expected proportions (directly proportional (+) or indirectly proportional (-)) and increased correlation coefficient, meaningful relations, where bearing capacity could be estimated, with extremely high correlation (r = 0.95 - 0.97) and containing basic material properties were obtained (Table 9). It should be indicated that these equations include basic mass and material properties such as seismic velocity, natural unit weight, point load strength, elastic modulus, Shore hardness, internal friction, and rock mass cohesion.

With the purpose of determining consistency of such equations obtained with measured bearing capacity, bearing capacities of the units worked on were reassessed according to equations (Equation 1-4) (Table 10).

In order to compare estimated bearing capacity values according to Equations 1, 2, 3 and 4 with measured bearing capacity values, simple regression analyses were performed. As a result of these regression analyses, relations with extremely high correlation (r = 0.97 - 0.98) were established between measured and estimated bearing capacities (Figure 3 and Table 11). It is beneficial to enhance these proposed bearing capacity equations through measuring’s held in different rock units.
Table 9. Multiple regression analysis results

| Independent Variablea | Bearing Capacity, Y (kg/cm²) | r   | Equation No. |
|------------------------|-------------------------------|-----|--------------|
| Seismic velocity (A)   | Y = -54.959 + 0.175*A + 6.916*B + 0.338*C | 0.95 | Equation 1 |
| Natural unit weight (B)| Y = -53.738 + 0.177*A + 9.073*B + 0.077*D | 0.95 | Equation 2 |
| Elastic modulus (C)    | Y = -44.715 + 0.166*A + 6.865*B + 0.166*E | 0.96 | Equation 3 |
| Point load strength (D)| Y = -42.846 + 0.171*A + 18.666*F + 1.591*G | 0.97 | Equation 4 |

a Seismic velocity, m/sn; Natural unit weight, gr/cm³; Point load strength, kg/cm²; Elastic modulus, GPa; Internal friction, °; Rock mass cohesion, kg/cm²

Table 10. Estimation of bearing capacity values using multiple regression analyses results

| Bearing Capacity, qυ (kg/cm²) | Studied Units | Measured | Equation 1 | Equation 2 | Equation 3 | Equation 4 |
|-------------------------------|---------------|----------|------------|------------|------------|------------|
| Magnetite                     |               | 110.49   | 109.373    | 109.336    | 109.515    | 108.671    |
| Syenite                       |               | 115.92   | 114.872    | 114.950    | 115.800    | 117.412    |
| Serpentinite                  |               | 97.71    | 103.546    | 103.360    | 102.538    | 100.730    |
| Limestone                     |               | 148.46   | 150.091    | 149.975    | 150.007    | 148.983    |
| Clayey limestone              |               | 119.48   | 114.258    | 114.178    | 114.480    | 114.653    |
| Dumping area                  |               | 130.71   | 93.441     | 96.358     | 96.053     | 102.162    |
| Gypsum                        |               | 63.01    | 23.791     | -          | -          | -          |
| Soil                          |               | 34.89    | 23.791     | 25.912     | 29.985     | 34.104     |

Figure 3. Relationship between measured bearing capacity and estimated bearing capacity (Equation 4)

Table 11. Relationships between measured bearing capacity and estimated bearing capacity using multiple regression analyses results

| Independent Variable, X | Measured Bearing Capacity, Y (kg/cm²) | r   |
|-------------------------|----------------------------------------|-----|
| Equation 1              | y = 3.0687X^{0.7757}                   | 0.97|
| Equation 2              | y = 2.4754X^{0.8185}                   | 0.97|
| Equation 3              | y = 1.6859X^{0.8993}                   | 0.97|
| Equation 4              | y = 1.0591X^{0.9962}                   | 0.98|
4. Conclusions
Bearing capacities of different rock units found in Sivas-Ulaş Open-Pit Celestite Mine, Divriği Open-Pit Iron Mine and Kangal Open-Pit Coal Mine around Sivas were calculated using some empirical formulas in the literature. With the purpose of comparing estimated and measured bearing capacity values, simple regression analyses were made. As a result of such regression analyses, relations with acceptable correlations ($r = 0.65 - 0.82$) were provided between measured and estimated bearing capacities (Table 6). Moreover, four different equations, through which bearing capacity could be estimated, were proposed considering also the parameters used in equations in the literature. Relations with higher correlation ($r = 0.97 - 0.98$) were provided in consequence of regression analyses held between estimated bearing capacities and those measured from these equations containing basic mass and material properties. It is seen beneficial to develop further these bearing capacity equations through measurements made for different rock units.

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