Vibration measurements for the prediction of ground bearing capacity

Atilla Ceylanoğlu[1] *and* ***Yavuz Gül***[1]

Instead of direct measurement, ground bearing capacity has been predicted by various equations in the literature. In this study, ground vibrations produced by a certain energy source were measured at eight different locations of three open-pit mines (Divriği Open-Pit Iron Mine, Kangal Open-Pit Coal Mine, and Ulaş Open-Pit Celestite Mine) in Turkey for the assessment of ground bearing capacity. Particle velocity values were evaluated considering the distance and the direction of the measurement. The paper reports a study depicting the use of vibration tests as a quick, cheap, and easy means of establishing a preliminary bearing capacity. The regression analyses indicated a clear relationship between the bearing capacity of rock formations ranging from weak to strong and the peak particle velocity with good performance indices (r^2, RMSE, VAF). The highest correlation coefficient was found at 0.97 where the distance to energy source was 7 m. Therefore, equation at a distance of 7 m was suggested for bearing capacity prediction.

Key words *ground bearing capacity, ground vibration tests, peak particle velocity*

Introduction

In surface mines, optimum equipment selection and road design should be made to get a reliable, economical and efficient haulage operation (Wyllie 1992; Bowles 1996). Determining the bearing capacity of working areas and roads is of great importance for the evaluation of drilling, digging-loading and transportation machines from the economy and safety points of view.

Rock units are generally assumed to be very good as foundation units. However, overloading leads to considerable subsidence or sudden failures in the foundations. Therefore, as in the 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. Numerous researchers have established various equations regarding determination of ground bearing capacity with analytical and empirical methods (Peck et al. 1974; Imai and Yoshimura 1976; Bell 1992; Wyllie 1992; Keçeli 1995; Hoek et al. 1995; Bowles 1996; Das 1999; Singh and Goel 1999; Şekercioğlu 2002; Aytekin 2004; El Naqa 2004; Singh and Rao 2005; Gül and Ceylanoğlu, 2006; Genç 2008; Alemdağ et al. 2008; Gül and Ceylanoğlu 2013; Alemdağ 2014; Ajalloeian and Mohammadi 2014; Haftani et al. 2014). In these relations, commonly uniaxial compressive strength, seismic velocity, rock mass rating (RMR), rock quality designation (RQD), geological strength index (GSI), internal friction angle, cohesion, discontinuity spacing, deformation modulus and natural unit weight were used. There are few relevant studies about empirical bearing capacity determination and easy, inexpensive and time-saving relations for rock units are very limited.

The bearing capacity of eight locations (magnetite, syenite, serpentine, limestone, clayey limestone, gypsum, soil and dumping area) was obtained by using a controlled plate loading test (Gül and Ceylanoğlu 2013). The vibration tests reported in this paper were undertaken at the same locations. Vibration testing, which was designed and applied to different rock units, has been found to provide an easy, quick and cheap means of predicting of the bearing capacity.

Geotechnical properties of studied units

An extensive two-year research programme was carried out systematically to determine the ground bearing capacity (ASTM D1194 1994; Ceylanoğlu and Gül 2004) of different rock units by using a plate loading test system (Gül 2006; Gül and Ceylanoğlu 2013) at three open-pit mine sites given in Table 1. Iron, coal and celestite open-pit mines are located in Sivas province, central Anatolia. Field studies, also based on the determination of some rock mass and material properties were undertaken on the rock benches (magnetite, syenite, serpentinite, limestone, clayey limestone, and gypsum) of these mines. Field study involved geotechnical description considering ISRM suggested methods (ISRM, 1978) and seismic survey. Table 1 presents the ground bearing capacities, rock mass rating values evaluated according to the Bieniawski 1981 and seismic primary-wave velocities of studied rock units.

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[1] *prof. Atilla Ceylanoğlu, MSc., PhD., assist. prof. Yavuz Gül, MSc., PhD.,* Cumhuriyet University, Mining Engineering Department, 58140-Sivas, Turkey, aceylan@cumhuriyet.edu.tr, ygul@cumhuriyet.edu.tr

Tab. 1. Results of geotechnical observations and in situ tests (Gül and Ceylanoğlu, 2013).

Location	**Studied Unit**	**Geotechnic Description**	**Bearing Capacity** [kg/cm²]	**Seismic Velocity** (P-Wave) [m/s]	****Rock Mass Rating, RMR** (Description, Class)	*****Ease of Digging/Ripping** (Weighted Class, Description)	**Rock Quality Designation** (RQD)
Sivas - Divriği Iron Mine	**Magnetite**	Dark gray, slightly weathered. Joint set No : 3 Average joint spacing : 3.0 m Stepped - smooth.	110.5	651	77 (Good Rock, II)	4 (Difficult)	93
	Syenite	Gray, fresh. Joint set No : 2 Average joint spacing : 0.4 m Planar - smooth.	115.9	752	64 (Good Rock, II)	3 Moderately Difficult	78
	Serpentine	Greeny gray, slightly weathered. Joint set No : 2 Average joint spacing : 2.0 m Stepped - smooth.	97.7	718	72 (Good Rock, II)	3 Moderately Difficult	92
Sivas - Kangal Coal Mine	**Limestone**	Light gray-brownish, slightly weathered. Average joint spacing : 1.5 m Undulating – rough.	148.5	1006	64 (Good Rock, II)	3 Moderately Difficult	92
	Clayey limestone	Cream to light brownish, moderately weathered. Average joint spacing : 0.8 m Undulating – rough.	119.5	814	49 (Fair Rock, III)	3 Moderately Difficult	84
	***Dumping area**	-	130.7	848	-	-	-
Sivas - Ulaş Celestite Mine	**Gypsum**	Light gray, slightly weathered. Joint set No : 2 Average joint spacing : 4.4 m Undulating – smooth.	63.0	1826	59 (Fair Rock, III)	4 (Difficult)	48
	Soil	Brown, completely weathered.	34.9	450	-	1 Easy	-

** Composed of limestone and clayey limestone soil pile turned into the road bed.*
*** Evaluated according to the Engineering Rock Mass Classification System (Bieniawski 1989)*
**** Ceylanoğlu et al. 2007*

Plate loading tests

Bearing capacity is defined as the maximum base pressure which can be conveyed to the ground without failure. The main laboratory apparatus of plate loading test are a hydraulic pump, pressure transducer, electronic displacement transducers, power inverter, battery, ground platens and the data logger. The laboratory apparatus and field set-up are shown in Figure 1. Set-up of plate loading test is formed in accordance with ASTM D. 1194-72 and TS 5744 standards (ASTM D1194-72 1987; TS 5744 1988). For assessing bearing capacity, plate loading tests had been performed on the same rock formations of this study.

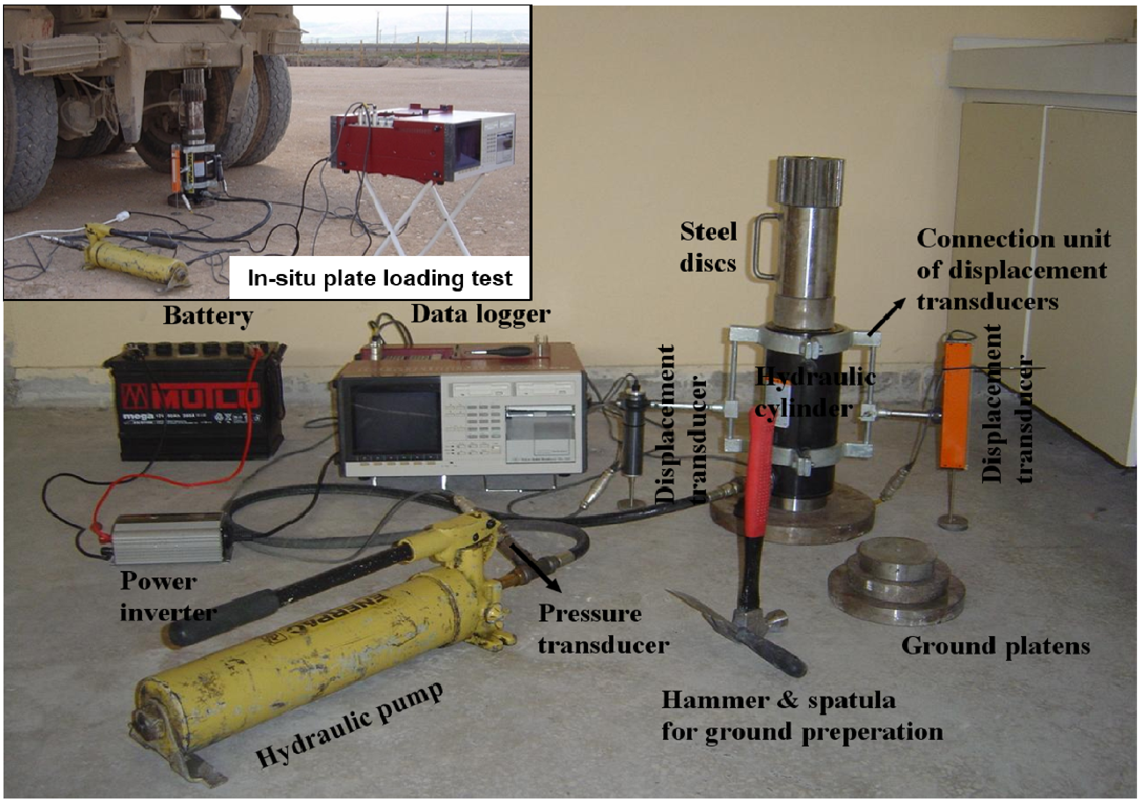

Fig. 1. Plate loading test equipment and field set-up (Gül and Ceylanoğlu, 2013).

Ground vibration field tests

Ground vibration in the rock environment induced by blasting or by a certain impact represents an energy transfer in the form of seismic wave motion from one point to another. As a result of this disturbance in the rock body, the surrounding elements lose their equilibrium positions and expose an oscillation movement similar to a drawn spring. During seismic wave motion in the rock body, there occurs no permanent strain in the rock mass (Dowding 1985; Karakuş et al. 2010). In other words, rock mass shows elastic behaviour during this motion. In this event, there are two different velocities where the first one is the seismic wave velocity and the second is the particle velocity due to oscillation.

Ground vibrations produced by a certain energy source were measured by vibration seismographs at the same locations of plate loading tests. The portable seismograph consisted of three geophones, microphone, control and memory unit, printer and battery. It used microcomputer technology. The particle velocity components (PPVT: transversal, PPPV: vertical, PPVL: longitudinal, PVS: sum and PPV: peak) were measured for each shot. As an energy source of ground vibration which is about 200 joule (8 kg * 9.81 m/s^2 * 2.5 m), the same worker dropped an 8 kg sledgehammer on a stiff polyester platen of 30 cm diameter and 5 cm thickness for each measurement. The worker dropped this hammer on the platen without applying any force during these shots (Fig. 2). In order to ensure that equivalent energy is produced, the sledgehammer was lowered by 1 1 different people at the same conditions. The test results showed that the peak particle velocity (PPV) values were nearly the same with a standard deviation of 2.21%. Since the peak particle velocity is a common parameter for most damage criteria, which have been established for different structures and cautious blast design and application, and various equations for peak particle velocity estimation have been developed in the literature, peak particle velocity values were used in this study. As is known, the peak particle velocity (PPV) is the highest of those, which are measured in three directions (transversal, vertical, longitudinal).

At each location, it was decided to measure the particle velocity components along four directions which are mutually perpendicular where the profile A-B being parallel and the profile C-D perpendicular to the bench face. The shot point is just at the center of (the intersection point) the profiles (Fig. 2). The distance between the energy source and the measurement station (place of the geophones) was increased by approximately 1±0.1 m intervals on the test profile due to difficulty in placing geophones. To increase the representative quantity of rock mass, the distance could be increased up to 7 m due to bench width and energy source limitations.

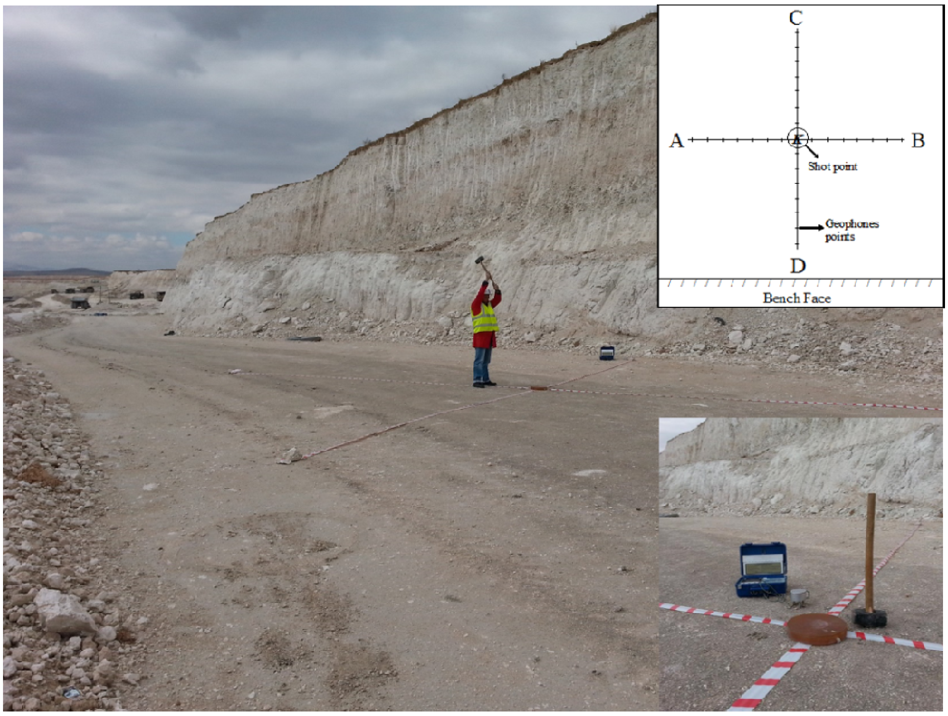

Fig. 2. Test profiles.

Starting from a point, ground vibrations are spread spherically. During this propagation they are subject to deflection/reflection depending on the characteristics of the encountered rock/soil traversed and eventually, they wither away. Measurement results revealed that values measured at the same distance along four different directions were very close to each other. Therefore, with the idea that it could be better to represent and characterize the studied units more accurately in specific distances, values measured along the same distances were averaged. By this way, average values of all particle velocity components were reached along different distances (1-7 m). Average PPV values of all studied ground types for various distances are given en masse in Table 2.

Tab. 2. Average peak particle velocity (PPV) values.

Studied Unit	Average Peak Particle Velocity [mm/s]						
	Distance [m]						
	1 m	2 m	3 m	4 m	5 m	6 m	7 m
Magnetite	24.25	13.95	10.09	8.02	6.71	5.80	5.13
Syenite	28.51	17.34	12.97	10.55	8.99	7.89	7.06
Serpentinite	36.99	17.13	10.92	7.93	6.19	5.05	4.26
Limestone	85.99	42.54	28.18	21.04	16.78	13.94	11.92
Clayey limestone	35.46	21.29	15.80	12.78	10.85	9.49	8.47
Dumping area	44.29	25.19	18.11	14.33	11.95	10.30	9.08
Gypsum	43.14	16.16	9.10	6.06	4.41	3.41	2.74
Soil	35.96	12.16	6.45	4.11	2.90	2.18	1.71

Evaluation of results

It is known that as the distance between the energy source and the measurement location increases the PPV values decreases. On the other hand, similar to bearing capacity and seismic velocity values, the rock mass properties such as joint spacing, the degree of weathering, stratification, compactness, grain size, moisture content influences the PPV values. As seen in Table 1, although the RMR value of the magnetite unit is high, its seismic velocity and PPV values are low. This can be explained by the effects of mentioned rock properties. In order to develop a relationship between the bearing capacity (Table 1) and peak particle velocity for all distances (Table 2), simple regression analyses were performed. The results are shown in Table 3. The regression analyses indicate a clear relationship between the bearing capacity and the peak particle velocity (Tab. 3, Fig. 3). The relationship between PPV and bearing capacity for a distance of 7 m was also given in Figure 4 to show the studied units in the figure of best relation. The highest correlation coefficient is found 0.97 where the distance is 7 m. Therefore, the equation of 7 m was suggested for bearing capacity prediction where the size of the mass is greatest and more representative than the others. However, in some cases where the rock bench width limits the distance, the relations of 3 - 6 m can also be used.

To check the prediction performance of the relationships obtained, variance accounted for (VAF) and root mean square error (RMSE) were considered (Alvarez and Babuska 1999; Finol et al. 2001; Gül and Ceylanoğlu 2013):

$$VAF = \left[1 - \frac{\mathrm{var}(y - y')}{\mathrm{var}(y)}\right] x100$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y - y')^2}$$

where y and y' are the measured and predicted values, respectively. The calculated indices are given in Table 3. If the VAF is 100 and RMSE is 0, then the model will be excellent. The obtained values of VAF and RMSE given in Table 3 indicated good prediction performances.

Tab. 3. Bearing capacity relationships and performance indices (RMSE, VAF and r^2).

Distance [m]	**Equation of Distances** **Y: Bearing Capacity** [kg/cm^2] **X: Peak Particle Velocity, PPV** [mm/s]	**Correlation Coefficient, r^2**	**RMSE**	**VAF** [%]
1	Y = 32.27*ln(X) - 15.644	0.11	95.94	80.03
2	Y = 74.269*ln(X) - 116.93	0.62	66.00	85.94
3	Y = 74.543*ln(X) - 86.861	0.84	65.84	86.26
4	Y = 68.873*ln(X) - 52.211	0.92	40.65	91.66
5	Y = 63.536*ln(X) - 25.733	0.95	23.14	95.20
6	Y = 59.176*ln(X) - 5.9067	0.96	11.22	96.77
7	Y = 55.658*ln(X) + 9.3078	0.97	5.83	97.16

RMSE = root mean square error, VAF= value accounted for

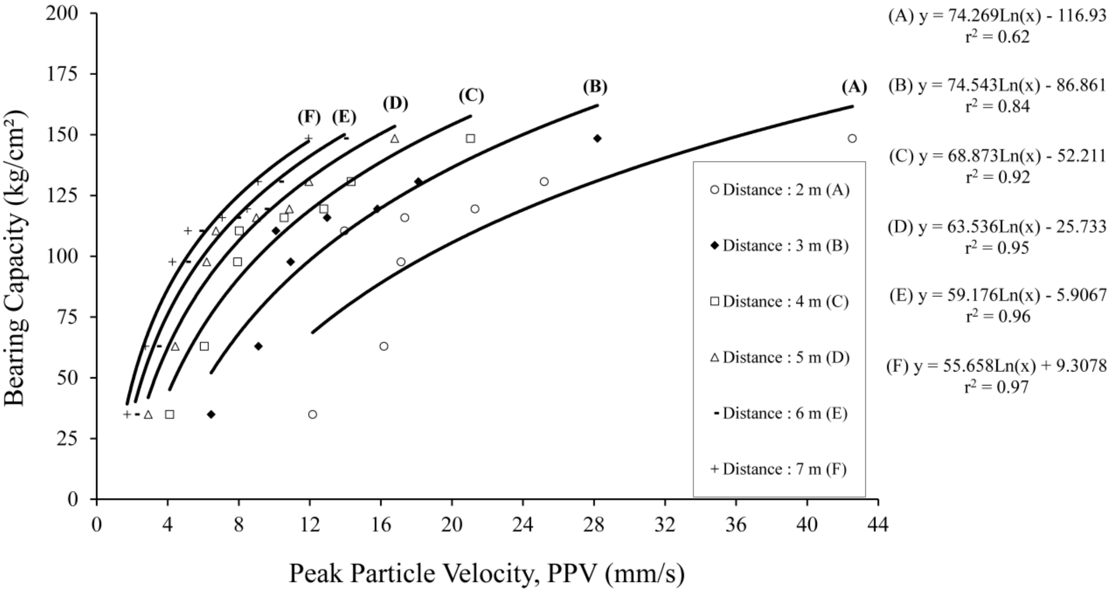

Fig. 3. The relationships between bearing capacity and peak particle velocity.

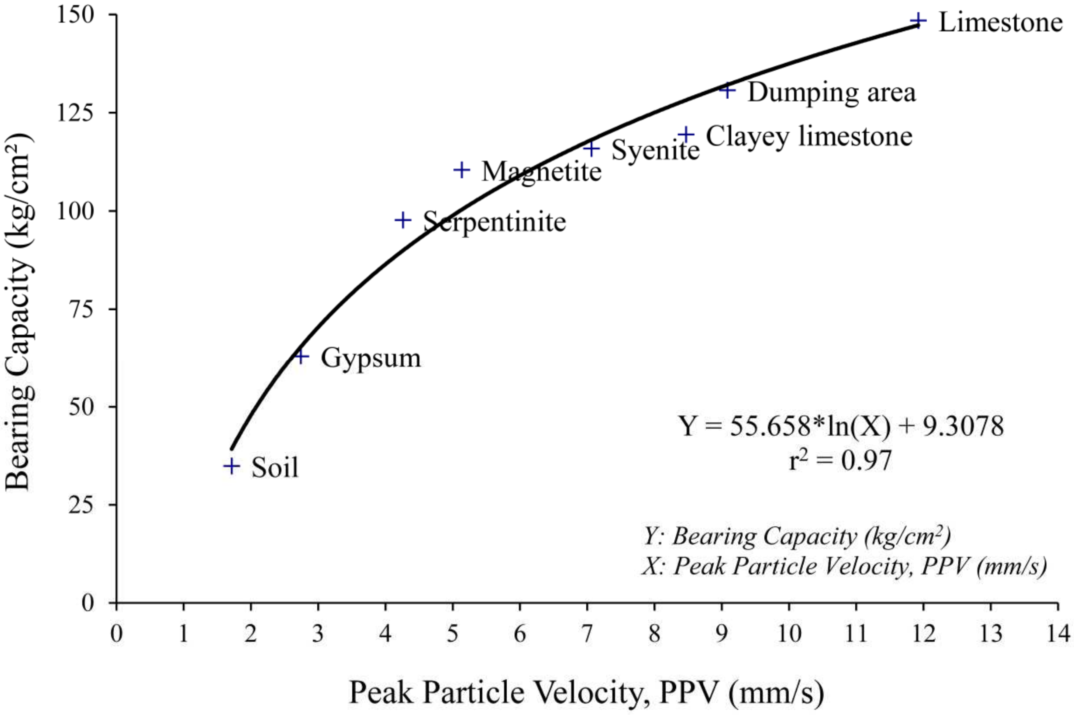

Fig. 4. The relationship between bearing capacity and peak particle velocity for distance 7 m.

Conclusions and recommendations

Although it is possible to establish the stability and efficiency of haul roads from basic in situ geotechnical tests, which include plate loading, the study investigated the use of vibration testing as a quick, easy and cheap alternative. A good relationship was found for magnetite, syenite, serpentine, limestone, clayey limestone, dumping area, gypsum, and soil; the exceptions being gypsum and dump soils. Without the need for a separate experimental set-up, the design engineers could easily estimate the bearing capacity of the grounds by using these relationships in a very short period of time.

The obtained relationships could be guiding and contribute in road design studies for mining and construction applications. Since the ground vibration measurement device is used for controlled blasting applications and monitoring the environmental impact of mining operations, it could also be utilized for the prediction of ground bearing capacity. The peak particle velocity appears to relate well to bearing capacity over a range of actual ground conditions. This quick, easy, inexpensive and time-saving alternative should be extended to a wide range of ground units for better prediction of bearing capacity.

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