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The Relation between Seismic Local Magnitude and Charge Weight for Quarry Explosions in Egypt

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Abstract: This study examines 32 quarry explosions which were recorded by the Egyptian National Seismological Network (ENSN) from Kottamya quarry area with a charge weight ranging from 1906 to 4326 kg of explosive material during the period from 2012 to 2013. This data is used to construct a relationship between the local seismic magnitudes (ML1.4 - 2.3) of these explosive events and their charge weight 'yield'. This relation will be used to estimate the yields of the explosions which will help for monitoring the quarry blasts that may cause damage to some structures. The empirical linear regression relation using these explosions is derived as follows ML = -0.33(±0.3) + 0.60(±0.1) log (W, kg). By correlating this relation with Gitterman's one, an agreement between the two at the lower charge weights was found. Therefore, the developed relation is extended to higher charges from the work of Gitterman and Shapira (2001) in order to have a relation of broader charges-range coverage. The new developed equation that combines both datasets is; ML = -2.79(±0.2) + 1.31(±0.06) log (W, kg).

keywords: Quarry explosions, Kottamya, Local magnitudes M_L, Charge Weight

1.Introduction

The Egyptian National Seismological Network (ENSN) plays a vital role in providing information on all seismic (natural and artificial) events occurring in Egypt. ENSN monitors these events using more than 75 seismological stations distributed all over the country. Most blasting (explosive) events in Egypt are carried out in quarry and mining areas in addition to others associated with the cement plants. Blasting activity may also be due to the construction of roads in remote areas. Among these sources is the Kottamya quarry area (Fig. 1)

The present study is focused on the quarry explosions in the Kottamya quarry area and recorded by ENSN. The purpose is to obtain a relation between local magnitudes; ML of these explosions and their charge weight 'explosion yield', measured in kilograms. We will also correlate the obtained relation with relationships in other areas. The magnitude-charge size relation will play an important role forensic seismology as well as in Comprehensive-Test-Ban Treaty (CTBT) monitoring and controlling quarrying activity (Koper et al., 2001; Bowers and Selby, 2009). Kottamya quarry is chosen to construct this relation as it is the unique one which provides detailed information on the explosion process. Its cement plant is one of the most important seismic artificial sources in Egypt which carry out periodic small chemical explosions. It is located in northern Egypt at 29.91° N, 31.53° E and occupies an area of approximately 4.2 km2 close to Cairo- El-Ain El-Sokhna road (Fig. 1). This quarry always uses Ammonium Nitrate/Fuel Oil (ANFO) and Gelatinous dynamites explosives for blasting which are usually detonated at a predetermined time sequence with milliseconds delays between successive shots.

There are various relations between ML and charge weights for different regions, and each quarry area has its specific relation which is different from the other areas. There is no clear linear relationship between magnitude and log (charge weight), even at individual quarries. This is quite common for chemical explosions particular mining and quarry area (Khalturin et al., 1998). The local magnitudes of the recorded explosions are calculated from the simulated Wood Anderson records which are extracted from the 3-component recordings of the seismic stations.

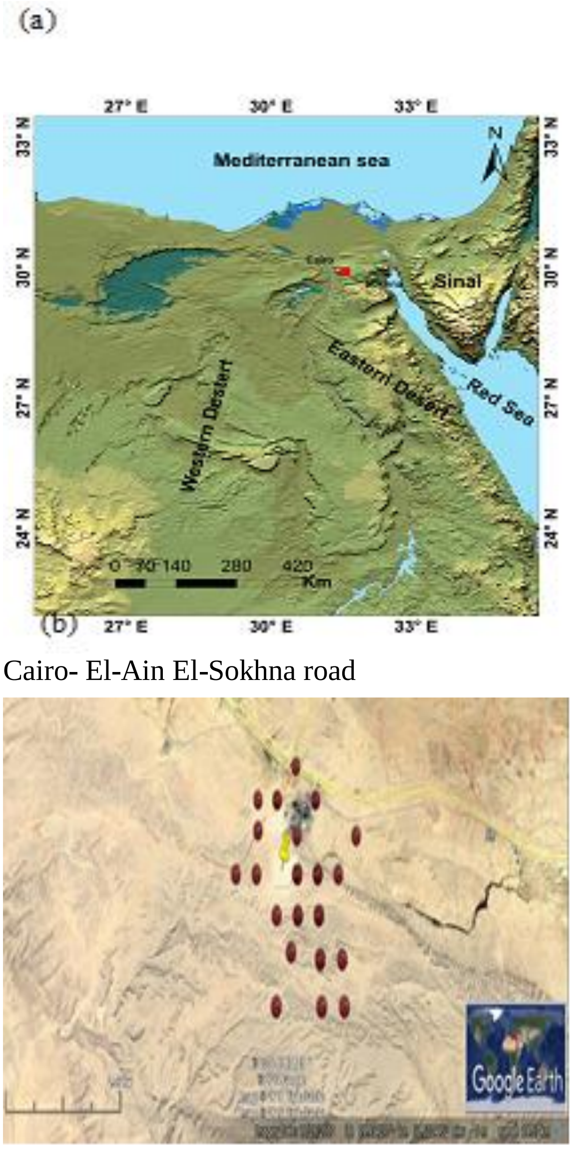

Fig. (1): (a) Location of Kottamya quarry area (red square), (b) Satellite image for Kottamya quarry area observed from Google Earth.

Data Collection:

The dataset for this study consists of digital velocity records of thirty-two quarry explosions with a high signal to noise (S/N) ratio for a two-years period; 2012- 2013. These explosions were conducted within Kottamya quarry area and recorded by some stations of ENSN. We obtained a list including the shot location, blasting time of explosions in local time, and the charge size of each explosion from Kottamya cement plant (Table 1). The explosions are located in different parts of the quarry. Figure (2) shows the location of the Kottamya quarry relative to the nearest ENSN stations. We used Hypoinverse2000 (Klein, 2000 and 2002) to analyze the explosions waveform data to determine the hypocenter location; epicentral distance, latitude, longitude, focal depth in addition to origin time and magnitude of each seismic event. Figure (1b) shows the locations of these explosions. The focal depths of all these 32 events are less than one km. Table (2) lists the stations of ENSN used for locating the explosion events. The waveform data is extracted from the database of Kottamya (KOT) and Hagoul (HAG) stations which are equipped with Streckeisen STS-2 broadband and short period SS-1 Ranger sensors, respectively. These stations have a set of 3-component seismometers aligned in; vertical, N–S, and E–W directions while the other stations are equipped with only a single vertical component. The availability of the two horizontal components (N-S, E-W) enabled to calculate the local magnitude. Therefore, stations having only a single component sensor are excluded.

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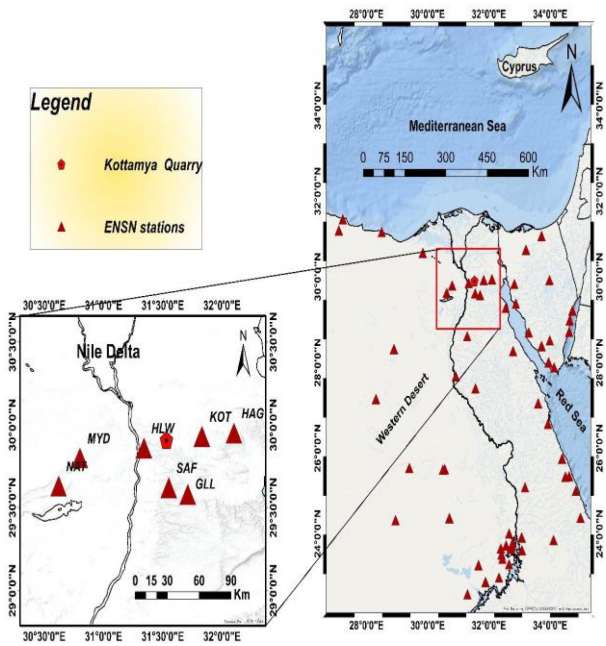

Fig. (2): Location of Kottamya quarry area and the nearest ENSN stations.

Table (1): List of the Kottamya – quarry explosions (including; shot location, blasting time of explosion, charge weight and other parameters for detonation) provided by the quarry operators

Date	Latitude(°N)	Longitude(°E)	Gel. kg	ANFO kg	Blasting Time of explosion
23/01/2012	29.93	31.53	600	2900	09:30
23/01/2012	29.92	31.54	1000	3920	09:35
01/02/2012	29.91	31.51	400	1780	09:00
01/02/2012	29.88	31.53	600	2900	10:22
01/02/2012	29.90	31.55	600	2900	10:25
28/02/2012	29.88	31.54	600	2900	09:20
28/02/2012	29.90	31.50	600	2900	09:25
20/03/2012	29.92	31.51	675	2760	09:00
20/03/2012	29.92	31.52	675	2760	09:15
24/04/2012	29.88	31.54	1000	3420	10:50
19/05/2012	29.89	31.53	737.5	3050	09:40
26/06/2012	29.92	31.54	925	3780	10:00
18/09/2012	29.88	31.55	450	2000	11:40
02/10/2012	29.87	31.54	750	3200	09:10
01/11/2012	29.89	31.54	455	1840	09:33
25/12/2012	29.90	31.53	386	1953	09:55
15/01/2013	29.91	31.56	596	2820	09:03
22/01/2013	29.90	31.54	551	2603	09:50
28/01/2013	29.87	31.55	375	2020	09:55
28/01/2013	29.90	31.53	350	1880	10:05
18/02/2013	29.89	31.54	583	2600	09:50
18/02/2013	29.90	31.53	583	2600	09:51
26/02/2013	29.89	31.53	582	2620	10:18
26/02/2013	29.90	31.54	609	2750	10:25
26/02/2013	29.87	31.52	609	2750	10:45
28/05/2013	29.89	31.52	625	2740	10:25
25/06/2013	29.89	31.54	700	2880	09:38
22/07/2013	29.90	31.54	680	2741	11:07
22/07/2013	29.90	31.53	680	2741	11:13
26/08/2013	29.91	31.53	595	2440	10:20
26/08/2013	29.92	31.52	595	2440	10:25
26/08/2013	29.90	31.51	525	3700	10.31

Table (2): Stations coordinates of ENSN that used in the study.

Station Code	Latitude (ºN)	Longitude (ºE)	Elevation (m)	Sensor Components
KOT	29.93	31.83	490	3C
HAG	29.95	32.10	477	3C
HLW	29.86	31.34	140	3C
GLL	29.58	31.71	519	1C
SAF	29.62	31.55	446	1C

2. Method of analysis:

The first step in this work is to convert the explosive charge into equivalent TNT charge using equation (1) because the latter is the most widely used. The following equation is used:

M_{TNTe}= (Eexp/E_{TNT}).M_{exp} (1)

This equation represents formulae for Ammunition Management (International Ammunition Technical Guideline, 2013).

Where:

M_{TNTe} = estimated TNT equivalent mass, (kg). *Eexp* = specific detonation energy of explosive (J/kg).

E_{TNT} = specific detonation energy of TNT (J/kg).

M_{exp} = mass of explosives in kg.

The second step, is the calculation of the local magnitude (M_L), based on the original Richter definition for estimating the magnitude. The local magnitude M_L for southern California earthquakes was formulated by Richter (1935 and 1958) as:

M_L= logA_{max}(WA)-logA_0 (2)

where A_{max} is the maximum amplitude in millimeters recorded by Wood Anderson horizontal seismograph (*WA*). Originally, this seismograph has a natural period of 0.8 seconds, a damping constant (h) of 0.8 and a static magnification (V) of 2800 (Anderson and Wood, 1925; Richter, 1935; Bakun et al., 1978; Uhrhammer and Collins, 1990). A_0 is a calibration term depending on the epicentral distance of the station Δ, which describes the peak amplitude decay with respect to distance in a certain region. Richter (1935 and 1958) constructed a calibration curve; logA_0 (Δ) for distance based on observations in California. This means that equation (2) is essentially valid for southern California. Using the same logA_0(Δ) for other areas will cause uncertainties in local magnitudes calculation. In order to overcome this problem, the Richter's equation must be corrected taking into consideration the differences in attenuation between southern California and other regions. This correction factor can be estimated in our region using the equation of (Ebel, 1982):

$\delta \log A_0 = \log\{\exp((\gamma_{sc} - \gamma_{ne})\Delta)\}$ (3)

where γ_{sc} and γ_{ne} is the spatial attenuation coefficients appropriate for southern California and northern Egypt, respectively. For southern California, the value of γ_{sc} at 1.7 Hz is equal to

0.0054/ km (Nutti, 1973) while γ_{ne} for northern Egypt is equal to 0.0077/ km at the same frequency (El Hadidy et al., 2006). Inserting the correction factor $\delta \log A_0$ into equation (1), the formula of the local magnitude will take the form:

$$M_L = \log A_{max}(WA) - \log A_0 - \delta \log A_0 \quad (4)$$

A number of calibration curves were constructed in sevral studies (Hutton and Boore, 1987; Vidal and Munguía, 1999; Renjifo and Anibal, 2004; Condori, 2017). Figure (3) shows the calibration curves that have been estimated in these previous studies in addition to this study. It is clear that all these curves have approximately similar values of *log*A_0 for epicentral distances located in the range between 0 and 200 km. The estimated curve for northern Egypt shows a relatively higher *log*A_0 values than the others for distances larger than 200 km. Equation (4) will be used to calculate the local magnitude value M_L for each recorded explosion in Kottamya quarry area from the simulated Wood-Anderson seismograms.

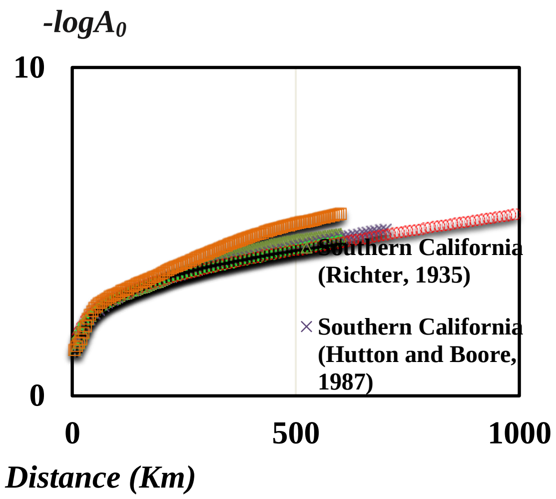

Fig. (3): Comparison of attenuation curves. The original relation for southern California (Richter, 1935; *as triangles*), Southern California (Hutton and Boore, 1987; *as x symbols*), Mexico (Vidal and Munguía, 1999; *as diamonds*), Colombia (Renjifo and Anibal, 2004; *as circles*), Peru (Condori, 2017; *as plus symbols*), and Northern Egypt (This study; *as squares*).

To calculate M_L, these sequential steps were followed; the digital waveform records of the explosions were processed to measure the maximum amplitudes from the two horizontal components. The waveform velocity records of both KOT and HAG stations were converted into simulated Wood-Anderson seismograms through deconvolution of the instrumental response in the frequency domain. Integrating in the frequency domain to obtain a displacement spectrum. Convolving this spectrum with the instrumental response of the Wood-Anderson seismometer. Then, converting the records back to the time domain. The final step is to measure the maximum recorded amplitudes observed on both the N-S and E-W components where an average value for each event is obtained. This analysis was performed using SAC (Seismic Analysis Code). Figure (4) shows samples of the recorded explosions and the simulated Wood Anderson seismograms for the two horizontal components.

After estimating the local magnitude for each explosion; using equation (4), the relation between TNT-equivalent charge weight (explosion yield) and the seismic magnitudes is investigated. We applied the linear regression least square fitting to derive the relationship between them. The classical relation between the yields and the magnitudes has the form: M = a log W + b (Khalturin et al., 1998), where (W) is the yield in kilograms (kg), (b) is a constant that may depend on the source medium but is independent on explosion yield and (a) is the slope of the magnitude yield curve.

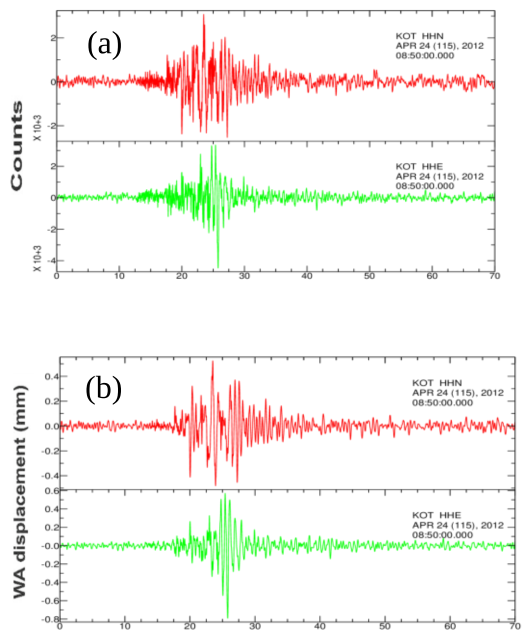

Fig. (4): (a) Seismogram of the original recorded explosion from the two horizontal components (N-S and E-W), respectively from

KOT station. (b) Simulated Wood-Anderson records for N-S and E-W components, respectively for KOT station.

Discussion and Conclusions:

There are several relations between the local magnitude and the yield of chemical explosions in different regions of the World. However, in case of quarry and mining explosions, each area has its specific relation. We estimated the yields of the explosions in three steps: 1) Calculating the local magnitude of the seismic event; then, 2) applying the distance corrections for the study region to compensate for differences resulting in using the M_L relation in another area rather than California; and finally, 3) Constructing the relationship between the local magnitudes and the yields of explosions using Khalturin's classical equation.

In this study, the local magnitudes of explosions are calculated using Richter's (1935, 1958) equation by measuring the average maximum peak-to-peak trace amplitude in millimeter from the two horizontal components of the simulated Wood Anderson records of the KOT & HAG stations. Then, the distance calibration term δ $\log A_0$ is applied to the local magnitude equation. The estimated values for this term are 0.03 and 0.04 for KOT and HAG stations, respectively. The estimated M_L values for these explosions ranged from 1.4 to 2.3 (Table 3). Before estimating the relation between explosives charge weights and the local

magnitudes, all charges should be converted into TNT equivalent charge weight (kg). The estimated values of charge weight W ranged from 1906 to 4326 kg (Table 3). The final step is to find an empirical relationship between local magnitude (M_L) and charge weight W (kg) using the 32 explosions at Kottamya quarry in performing the least square fitting. The obtained empirical relation has the form: M_L = - 0.33 + 0.60 log (W, kg) with a correlation coefficient R^2 = 0.80 which approaches to 1. This means that the degree of fittness is well (Fig. 5). The root mean square error is 0.094 and the standard deviation (σ) of the linear regression is 0.109. The obtained relation (Fig. 5) shows the general and logic trend for magnitude to increase with charge weight. Comparing this equation (Eq. 3, Fig. 6) with the other quarry equations (Eq. 1 and 2, Fig. 6) in Israel and Jordan for different explosive sources (Table 4), shows that our relation is very close to that of Gitterman and Shapira, 2001 (Eq. 2, Fig. 6). This relationship was derived from the single fired quarry blasts of Israel in addition to concure nt land explosions (Fig. 6).

Table (3): Estimated parameters of the recorded Kottamya quarry explosions using KOT and HAG stations.

Event Date	Blasting Time	Estimated ML(HAG)	Estimated ML(KOT)	ANFO. to (TNT)	Gel. to (TNT)	TNT equivalent charge weight Kg
23/01/2012	09:30	1.59	1.70	2410.470	641.026	3051.496
23/01/2012	09:35	1.87	1.72	3258.291	1068.36	4326.66
01/02/2012	09:00	1.49	1.52	1479.530	427.350	1906.880
01/02/2012	10:22	1.86	1.67	2410.470	641.026	3051.496
01/02/2012	10:25	1.80	1.61	2410.470	641.026	3051.496
28/02/2012	09:20	1.89	1.73	2410.470	641.026	3051.496
28/02/2012	09:25	1.76	1.67	2410.470	641.026	3051.496
20/03/2012	09:00	1.87	1.77	2294.103	721.154	3015.256
20/03/2012	09:15	1.89	1.76	2294.103	721.154	3015.256
24/04/2012	10:50	1.83	1.81	2842.692	1068.36	3911.068
19/05/2012	09:40	1.87	1.69	2535.150	787.927	3323.077
26/06/2012	10:00	1.71	1.63	3141.923	988.248	4130.171
18/09/2012	11:40	1.90	1.68	1662.393	480.769	2143.162
02/10/2012	09:10	1.87	1.72	2659.829	801.282	3461.111
01/11/2012	09:33	1.60	2.01	1529.402	486.111	2015.513
25/12/2012	09:55	1.71	1.82	1623.327	412.393	2035.720
15/01/2013	09:30	1.89	1.97	2343.976	636.752	2980.728
22/01/2013	09:50	1.72	1.75	2163.606	588.675	2752.281
28/01/2013	09:55	1.81	1.63	1679.018	400.641	2079.659
28/01/2013	10:05	1.69	1.62	1562.650	373.932	1936.582
18/02/2013	09:50	1.69	1.64	2161.112	622.863	2783.975
18/02/2013	09:51	1.84	1.74	2161.112	622.863	2783.975
26/02/2013	10:18	1.79	1.66	2177.736	621.795	2799.531
26/02/2013	10:25	1.69	1.61	2285.792	650.641	2936.433
26/02/2013	10:45	1.93	1.69	2285.792	650.641	2936.433
28/05/2013	10:25	1.81	1.67	2277.480	667.735	2945.215
25/06/2013	09:38	1.88	1.55	2393.847	747.863	3141.711
22/07/2013	11:07	1.88	2.31	2278.311	726.496	3004.807
22/07/2013	11:13	2.01	1.54	2278.311	726.496	3004.807
26/08/2013	10:20	1.75	1.57	2028.121	635.684	2663.804
26/08/2013	10:25	1.57	-	2028.121	635.684	2663.804
26/08/2013	10:31	1.96	1.93	3075.429	560.897	3636.326

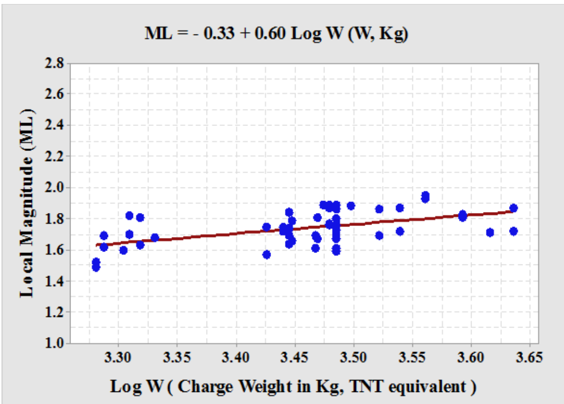

Fig. (5): Local magnitude vs. charge weight (yield) for quarry explosions fired at Kottamya quarry.

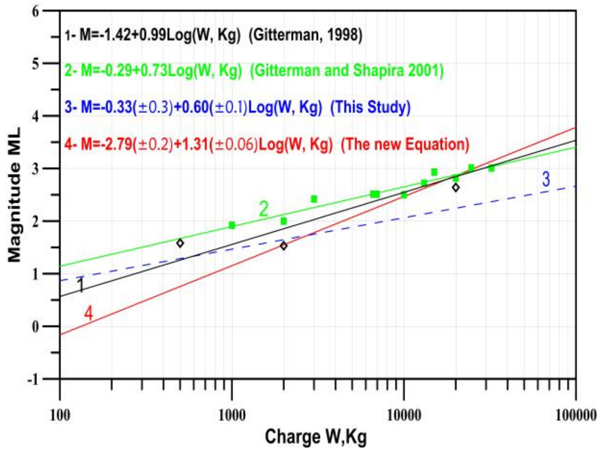

Fig. (6): Different relations between magnitude and explosive charge weights including different types of explosive sources in Jordan and Israel.

Table (4): Empirical relations for different types of explosives in different regions.

No.	Equation	Source
a	M = -1.42 + 0.99 Log (W, Kg) (Gitterman, 1998)	Single shot blasts in Israel quarries.
b	M = -0.29 + 0.7327 Log (W, Kg) (Gitterman and Shapria, 2001)	Quarry explosions in Israel and Jordan.
c	M = -0.33(±0.3) +0.60(±0.1) Log (W, Kg) (This study)	Kottamya Quarry explosions, Egypt.
d	M = -2.79(±0.2) + 1.31(±0.06) Log(W, Kg)	New equation that developed by combining both datasets of equations b and c.

As a result of this agreement between the two equations at lower range of charges, we used the dataset of Giterman and Shapira's equation for higher charges that ranged from 6620 to 32300 kg to develop a new equation covering a wider range of charges. The new equation (Eq. 4, Fig. 6) has the form M_L = -2.79(±0.2) + 1.31(±0.06) log (W, kg) with a correlation coefficient R^2 = 0.95 which is close to 1 and with a root mean square error value of 0.12. We conclude also that each region has its specific relation for quarry explosions.

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