

Geological impact on seismic attenuation and earth-quake damage: Case of L'Aquila earthquake (2009)

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Abstract. You The quality factor of waves is a key index of the accuracy of seismic wave absorption types, which is influenced by several factors among them on geological characteristics. This article confirms this relationship by analyzing the major earthquake of April 6, 2009, that occurred in Italy specifically in L'Aquila, with a magnitude of 6.3 ML, causing 308 deaths. This earthquake damaged between 10,000 and 15,000 buildings spread across 26 locations. This earthquake was a main cause for modifying seismic standards by giving more importance to soil types in each region. The 12 seismic events analyzed in this study are recorded with 7 stations located less than 7 km from the hypocenter, ensuring accuracy in the results obtained. This distance is less than 250 km, which is the maximum limit for this type of study, L'Aquila is made up of geological contrasts, with hard limestones being more dominant in the substrate of the Apennines, this type of limestone has led to low wave absorption, favoring an efficient transmission of seismic energy. However, this low energy dissipation has caused powerful ground vibrations, amplified by the loosely consolidated superficial sedimentary layers. This observation is justified by the obtained average regional attenuation relationship:

$$Q(f) = 86.1 \pm 13.6. f^{1.03 + 0.05}$$

Keywords: Quality factor, L'Aquila Earthquake, Attenuation.

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1 Introduction

In the tectonic history of Aquila, we find that this diverse region has been hit by several major seismic events, but the Aquila earthquake (2009) was the most severe, with a high rate of damage to the city and its surroundings (Galli et al., 2010). Several parameters influence the attenuation of seismic waves. We start with the geological characteristics related to the nature of the soil; a hard soil, such as the massive lime-stone of Aquila, results in low attenuation of seismic waves due to its structure (Field et al., 1992). On the other hand, a soft soil composed of loose sediments absorbs seismic energy better, especially at high frequencies (Fu Zhanling., 2021). Similarly, the depth of the earthquake has an influence, a shallow earthquake (< 30 km) causes more destructive waves at the surface, because they are close to the Earth's crust (USGS (2020)). Also, a high magnitude reflects a powerful earthquake and in the majority of cases produces more damage. Faults of several types can also be found there, such as the normal fault which was a direct cause of the Aquila earthquake (Chiarabba et al. (2009) (Chiaraluce, L., et al. (2011))). In addition, the geological structures of the surface layers, such as fractured limestones and schists, impact the propagation of waves, making attenuation more complex in certain areas (Iervolino et al., 2010). The objective of this study is to estimate the quality factor in the Aquila region for the two existing soil types

2 GEOLOGICAL CONTEXT OF THE L'AQUILA REGION

L'Aquila is a region located in the central Apennines in Italy. Characterized by geological heterogeneity. Its lithology contains two types of rocks, sedimentary and metamorphic. It is known for its active faults in the Apennine chain, such as the Paganica fault, and for its amplifying alluvial sediments that make the area tectonically active Biella et al. (1987). These faults increase the intensity of seismic tremors, causing ruptures that generate large amounts of energy and intensifying the effects of earthquakes (Barchi et al., 2000). In the L'Aquila valley, the impact of earthquakes can be significantly amplified. In urban areas, poorly consolidated sediments allow for intense propagation of seismic waves, amplifying the tremors. Furthermore, the geological structures of the surface layers, such as fractured limestones and schists, modify the propagation of waves, making attenuation more complex in certain areas (Iervolino et al., 2010). The tectonic context of the region is dominated by an extension regime, with active faults (Boncio et al. (2010) such as the Paganica and Sassa faults extending over a large part of the Apennines (Walters et al., 2009). The latter are responsible for the frequent seismic tremors in the region.

3 DATA

In order to study the attenuation in the Abruzzo region of Italy, we selected several events before and after the L'Aquila earthquake in 2009. The main event of April 6, 2009, is included; see Table 2. These events were recorded at four stations. Table 1 presents the coordinates of these stations as well as the recording network. A map has been created to show the location of stations (blue triangles: stations) and events (red circles, whose size is proportional to magnitude) in Figure 1.

Table 1. Stations used to estimate the quality factor for this study

Network	Station	Latitude(°N)	Longitude(°W)
8H	RM02	42.40	13.41
8H	RM07	42.33	13.30
8H	T0102	42.40	13.31
8H	T0103	42.36	13.42
4A	MI03	42.33	13.48
4A	MI02	42.35	13.47
IV	AQU	42.38	13.32

Table 2. List of events selected for coda Q estimation in the L'Aquila region, Italy

Origin Time	Magnitude (ML)	Latitude (°N)	Longitude (°W)	Depth (km)
2009-04-07T21:34:29	4.6	42.38	13.38	7.4
2009-04-07T09:26:28	4.8	42.34	13.39	10.2
2009-04-06T22:47:13	4.1	42.35	13.29	11.6
2009-04-06T21:56:53	4.1	42.4	13.32	9.7
Origin Time	Magnitude (ML)	Latitude (°N)	Longitude (°W)	Depth (km)
2009-04-06T16:38:09	4.3	42.36	13.33	10.2
2009-04-06T07:17:10	4.3	42.35	13.37	9.2
2009-04-06T04:47:53	4	42.35	13.35	9.4

2009-04-06T03:56:45	4.4	42.34	13.39	10
2009-04-06T02:37:04	4.9	42.37	13.34	10.1
2009-04-06T02:27:46	4.2	42.37	13.34	10
2009-04-06T01:32:39	6.3	42.33	13.33	8.8
2009-04-05T20:48:54	4.0	42.33	13.37	8.4

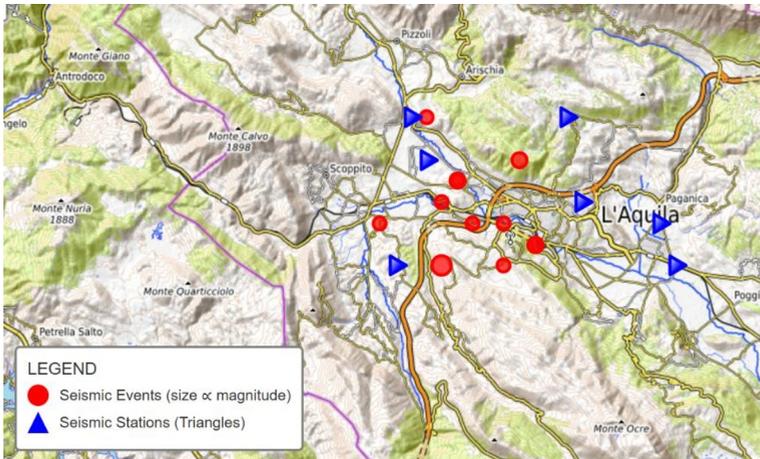


Fig. 1. Stations and events (red circle: events -blue triangles: stations)

4 METHOD OF CALCULATION OF ATTENUATION OF SEISMIC WAVES

Seismic wave attenuation is a frequency-dependent parameter calculated using the following equation (Aki et al., Chouet (1975)):

$$Q(f) = Q_0 \cdot f^n \tag{1}$$

- n : is an exponent that depends on the medium

To estimate the attenuation parameters, we use the single backscattering model of Aki and Chouet (1975), expressed by the following equation:

$$A(f, t) = S(f) \cdot t^\alpha \cdot \exp\left(-\frac{\pi \cdot f \cdot t}{Q_c(f)}\right) \tag{2}$$

- $A(f, t)$ is the amplitude of the coda wave
- $S(f)$ represents the source factor of the coda wave at frequency

- α is the geometric spreading parameter

5 RESULT AND DISCUSSION

Table 3. Qc values as a function of frequency for different seismic stations

Station	Frequency (Hz)	Qc (20s)	Qc (30s)	Qc (40s)	Qc (50s)
AQU	0.75	55.93	60.24	65.96	66.03
AQU	1.5	120.94	118.15	130.67	132.68
AQU	3	243.54	237.03	262.86	262.59
AQU	6	483.56	475.56	520.76	529.61
AQU	9	912.63	948.79	978.56	999.26
RM02	0.75	60.15	65.87	69.81	70.25
RM02	1.5	118.04	124.98	136.93	140.70
RM02	3	239.21	247.02	276.02	279.25
RM02	6	480.53	509.39	547.99	562.92
RM02	9	962.53	970.99	1000.93	1110.64
RM07	0.75	59.43	63.40	70.53	80.25
RM07	1.5	118.23	127.08	142.09	160.90
RM07	3	235.82	257.17	286.01	322.12
RM07	6	471.60	515.36	572.00	644.20
RM07	9	933.30	999.70	1040.00	1001.88
T0102	0.75	50.24	60.45	82.19	87.25
T0102	1.5	100.12	117.90	162.12	174.65
T0102	3	200.54	241.82	304.19	299.89
T0102	6	412.56	483.40	600.18	597.98
T0102	9	725.32	760.36	820.08	880.51
T0103	0.75	50.19	70.15	78.16	88.29
T0103	1.5	102.13	139.81	138.12	152.82
T0103	3	205.18	265.05	275.90	289.45
T0103	6	415.10	498.19	589.23	589.99
T0103	9	720.65	770.36	812.67	889.78
MI03	0.75	56.00	60.40	70.30	76.70
MI03	1.5	99.10	120.90	103.98	149.55
MI03	3	203.70	237.17	230.39	254.27
MI03	6	408.34	505.86	537.14	556.48
MI03	9	816.27	829.43	897.31	900.34
MI02	0.75	48.19	59.18	67.11	70.90
MI02	1.5	98.90	105.01	109.21	142.34
MI02	3	204.10	251.12	278.09	285.76
MI02	6	407.18	519.98	543.45	573.13
MI02	9	700.12	721.70	763.17	800.19

Analysis of Qc values shows a general increase in the quality factor with depth, represented here by the lengthening of the time lapse (from 20 s to 50 s), which reflects a decrease in geological heterogeneity at depth. Stations such as AQU, RM02, RM07 or T0102 show a progressive increase in Qc, especially at high frequencies, indicating that deeper layers are

more rigid and homogeneous. This is consistent with the study by El Fellah et al. in 2019 and Timoulali et al. in 2014 that high Q values at a depth of more than 30 km are related to higher seismic wave speed. Therefore, the delta Q_c between stations reflects the structural complexity of the Earth's crust and the direct dependence of depth on attenuation.

Table 3. Estimation of quality factors at different frequencies and for different soil types

Station	20s (Q_0 / n)	30s (Q_0 / n)	40s (Q_0 / n)	50s (Q_0 / n)
AQU	75.7228 / 1.09056	77.4639 / 1.07756	85.8175 / 1.05921	86.1660 / 1.06552
MI02	64.3904 / 1.06112	76.3290 / 1.04137	84.0196 / 1.01966	95.3618 / 0.98402
MI03	68.8375 / 1.05588	79.2840 / 1.04633	80.4709 / 1.05332	97.9917 / 0.97705
RM02	77.4069 / 1.08432	83.4623 / 1.05945	90.6589 / 1.04990	91.1749 / 1.07826
RM07	76.9617 / 1.07558	82.6474 / 1.08031	92.6963 / 1.06006	106.7640 / 1.01153
T0102	65.7170 / 1.05783	79.5120 / 1.01721	109.3100 / 0.93187	114.8880 / 0.92006
T0103	66.4820 / 1.05467	93.1292 / 0.95262	98.6538 / 0.96592	109.3200 / 0.93703

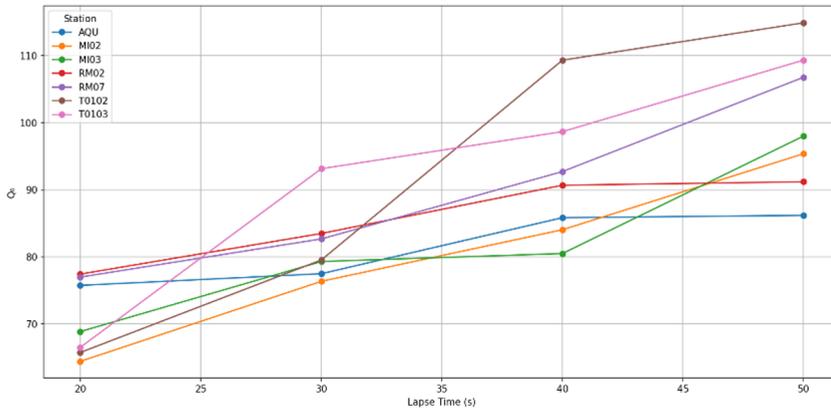


Fig. 2. Plot of Q_0 with lapse time for all stations.

Attenuation analysis across different seismic stations and time lapse times shows that the quality factor Q_c increases with frequency, following relationships such as $Q_c(f) = 70.79 \cdot f^{1.06}$ (20 s), $Q_c(f) = 81.69 \cdot f^{1.04}$ (30 s), $Q_c(f) = 91.66 \cdot f^{1.02}$ (40 s), and $Q_c(f) = 100.24 \cdot f^{0.62}$ (50 s). These results are consistent with previous studies, such as S. de Lorenzo et al. (2013), who proposed $Q = 80.6 \cdot f^{0.7}$. Based on this, we identified two average relationships by soil type, $Q_c(f) = 92.7 \cdot f^1$ for rocky soils, and $Q_c(f) = 82.1 \cdot f^{0.98}$ for soft soils, these two empirical models were used to derive a regional average attenuation law, expressed as: $Q(f) = 86.1 \pm 13.6 \cdot f^{1.03 + 0.05}$

The results also show that Q_0 increases and the frequency exponent n decreases with increasing time intervals, indicating lower attenuation at greater depths.

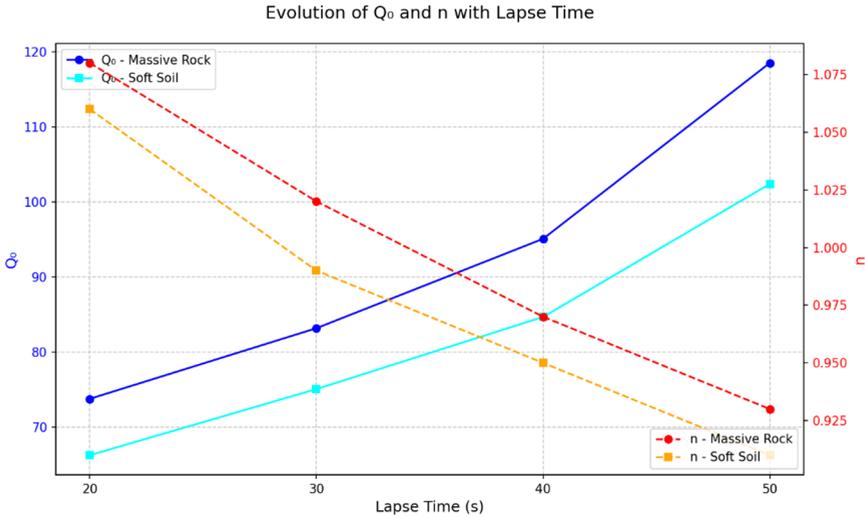


Fig. 3. Average evolution of Q_0 and n as a function of lapse time

6 CONCLUSION

The geological and seismic study of the L'Aquila region highlights the impact of local geological characteristics on seismic wave propagation. The observed attenuation results highlight the impact of soil type on tremor amplification. This must be taken into account during design to avoid the risk of damage caused by earthquakes.

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