A Physical ground for the scaling of Peak Ground Acceleration (PGA) with the integral of squared velocity \( (I^2_{Vp}) \) and its potential for Earthquake Early Warning

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Abstract. One of the main goals of an Earthquake Early Warning System (EEWS) is to estimate the expected peak ground motion of the destructive S-waves using the first few seconds of P-waves, thus becoming an operational tool for real-time seismic risk management in a short timescale. EEWSs are based on the use of scaling relations between parameters measured on the initial portion of the seismic signal, after the arrival of the P-wave. Scope of the present work is to study the physical basis of the scaling laws observed between the peak ground acceleration (PGA) and the integral of the squared velocity \( (I^2_{Vp}) \). Based on Brune’s model, which is one of the most widely adopted earthquake source models, we explore the physical principles of the scaling relations between the root mean square (rms) of the velocity acceleration recorded in the first few seconds after P-wave arrival and acceleration (recorded in S-waves) and the \( I^2_{Vp} \). Assuming a relation between the PGA and the rms values estimated, the scaling of PGA with the integral of the squared velocity \( (I^2_{Vp}) \) which is calculated directly from the first few seconds-long signal window \( (T) \) after the P-wave arrival obtained. The latter formulation opens the possibility of using such laws for on-site and inter-site earthquake early warning.

1. Introduction

Advances in signal processing, data communications and real-time seismology have gradually rendered the concept of a reliable Earthquake Early Warning System (EEWS) a possibility [1-17]. Damages from an impending strong motion can be reduced by taking mitigation measures suitable for the given warning time [5, 6]. EEWSs have already been deployed, whether operationally or at a pilot stage, in Japan [1, 3, 16], Mexico [18], Taiwan [19], Greece [20, 21], Italy [22-24] and California, USA [25, 26]. A detailed and comparative analysis of the performance of EEWS in Europe is given in [27, 28] while a recent application in the Northern California rail system is presented in [29].

An earthquake generates two fundamental types of body-waves: longitudinal (P) and shear (S) waves. The direct P-waves are weaker in amplitude and have a higher velocity than the S-waves. As a result, the difference in velocity can be used to retrieve information about the earthquake from the first wave arrivals and, consequently, predict the effect of the impending destructive secondary waves [10].

Earthquake early warning systems can mainly be divided into two categories: (a) on-site and (b) regional, even though the combination of both has also been explored [30-34]. The on-site EEWSs use one seismic station to offer insight about individual sites (such as critical infrastructure), e.g. [26, 29]. Regional EEWSs use multiple P arrivals to estimate the epicenter and magnitude of the earthquake.
and provide information for the affected area, e.g. [21, 22, 25, 33, 34]. This poses fundamental differences in the design, operation, and maintenance of the system. The on-site approach can give a larger warning time, but is susceptible to false triggers and local site effects. Regional EEWSs offer more robust estimations, but are affected by errors in the source estimation and require a large investment in seismic network design and deployment.

The regional EEWS, based on the operation of a regional network that detects earthquake events, locate them and determine its magnitude, using for the analysis the first few seconds of the arrivals of the P waves recorded at the stations [35, 36, 37]. In contrast the on-site system consists of a single or more sensors in the vicinity of target area or sometimes inside the structure under interest to be alerted. In the on-site approach the P-wave recordings to the seismic sensor are used to predict the peak ground motion at the site [16]. The on-site approach could be useful for sites located within the blind zone of a regional EEW system, creating a warning before the arrival of strong shaking S-waves. Worth to mentioned that in a number a applications the two EEW approaches combined [38, 39, 40] in a way that local parameters and predicted ground motions at a regional scale could be capable to provide accurate and even rapid estimations of the parameters of earthquake source along with the size of the expected damage zone [30].

The regional EEW can be analyzed in terms of the geometry of the source following two main views. The first one assumes a point-source where the earthquake source viewed as a concentrated volume, while in the second approach a finite fault introduced and thus we take into consideration the entire fault area. Most studies have used the “point-source” demonstrating the reliability of this approach for the magnitude estimation of small to moderate events. However, it has been shown that this approach is not always accurate for strong earthquakes with magnitude greater than 7, due to the saturation of the P-wave parameters [16, 41]. In the present work we use the point-source approach and our results are limited to earthquakes with a moderate magnitude (≤ 6.5) that could be considered as point sources.

Scaling laws are of fundamental importance in EEWSs, as they connect early estimated parameters with the strength of impending S-wave. Relations between the integral of squared velocity estimated from the initial P-wave \(I_{vp}^2\) and a metric of the anticipated shaking, such as the macroseismic intensity or the ground’s acceleration during a seismic event, have been proposed [31-42].

The integral of squared velocity [42] is defined as:

\[
l_{vp}^2 = \int_{t_p}^{t_p+T} V^2(t)dt
\]  

where \(t_p\) the P arrival time, \(T\) the considered signal window and \(V(t)\) the signal in velocity terms [33] estimated from the initial P wave. Therefore, a relation between \(l_{vp}^2\) and the Peak Ground Acceleration of S-waves (PGA) [33, 34] can be given as:

\[
\log(\text{PGA}) = a + b \times \log(l_{vp}^2)
\]

which suggests that we can predict the shaking using the initial P waves. Albeit equations similar to (2) have been used to connect \(l_{vp}^2\) to earthquake strength metrics in a single site, using a sensor near the source to obtain the latter and extrapolating the value of PGA in another target site could provide a significant warning time advantage [34].

In this work, we analyse the physical base of the scaling expression (2), focused on the correlation of \(l_{vp}^2\) with PGA on-site and inter-site, using Brune’s model, one of the most widely adopted earthquake source models [43]. Determination of the strength of shaking from the initial P-wave is an important element for earthquake early warning, since PGA is a quantity commonly used in seismic risk and engineering, e.g. [44].

2. Empirical Scaling laws between PGA and \(l_{vp}^2\)
A regional EEWS operates analyzing the information from the seismic network deployed in the vicinity to the epicenter and predicts the regional seismic intensities using a ground motion prediction equation [35]. On the other hand, the on-site system often consists of seismic stations located at particular target sites of interest, providing rapid ground motion estimates, using only information on the characteristics of P waves recorded at one seismic station [10], since a number of empirical relationship used to algorithms that derive ground shaking [45, 46, 47].

The parameter $I_{VP}^2$ was first introduced in [42] to estimate the earthquake magnitude, providing good correlation between the two quantities. Recently, a correlation between $I_{VP}^2$ and PGA was reported [20, 21]. The relationship between $I_{VP}^2$ and PGA could therefore be used to identify, in real-time and before the arrival of S waves, whether a site is going to be adversely affected or not, and, thus, has the potential to become key in the design of on-site or inter-site EEWSs, enabling automatic mitigation measures and assisting civil protection in acting immediately, according to the severity of the situation. We note that the reliability of the scaling between $I_{VP}^2$ and PGA has been recently tested and extensively used to establish EEWS [31, 42].

Figure 1 presents PGA as a function of $I_{VP}^2$ in the on-site case of some stations in Greece. For all the cases, a correlation as that of equation (2) exists, while $b$ is quite stable close to 0.5. It is noted that while $I_{VP}^2$ is computed from measurements in the vertical channel, PGA refers to the maximum observed acceleration between the two horizontal components of the sensor.

$$a = 1.480 \pm 0.148$$
$$b = 0.491 \pm 0.026$$

Figure 1. Scaling of PGA with $I_{VP}^2$ for stations (a) HT.LIT (red squares) and (b) HA.ATHU (blue dots) using a T=3s time windows after the P-wave arrival. PGA is estimated from the maximum amplitude of the two horizontals after the S-wave arrival, while $I_{VP}^2$ is obtained from the vertical channel. Both stations are located in Greece. For details see [33, 34]. Values for the intercept and slope of equation (2) are given, along with their standard errors (top left).

The potential of $I_{VP}^2$ as an inter-site tool has been demonstrated in [20, 21], by measuring it at a reference station located closest to earthquake sources (named $I_{VP}^{2\text{close}}$) and relating it to PGA at target sites (PGA$^{\text{ts}}$) using a scaling relation of the form of equation (2), i.e.,

$$\log(\text{PGA}^{\text{ts}}) = a + b \cdot \log(I_{VP}^{2\text{close}}).$$
Examples of such relations are given in Figure 2.

![Figure 2](image)

\[ a = 0.742 \pm 0.245 \\
\[ b = 0.401 \pm 0.052 \]

**Figure 2.** PGA in target site Athens (stations HA.ATHU and HL.ATH) that scaled with \( I^{2} \) measured at reference stations at Loutraki (HA.LOUT and HP.LTK), using a \( T=3s \) time windows after the P-wave arrival. Both sites are located in Greece (see [33]). Values for the intercept and slope of equation (2) are given, along with their standard errors (top left).

From Figures 1 and 2 it is obvious that expression as that of equation (2) could fit the observed data satisfactorily. The physical basis of such an expression is still an open question, along with the source and medium parameters that control the fitting coefficients \( \alpha \) and \( b \) in equation (2). This question will be addressed in the next paragraph.

### 3. On the Physical basis of PGA- \( I^{2} \) scaling law

To establish a relation between the strong ground motion parameters and \( I^{2} \) we will use the root mean square (rms) value of the velocity and acceleration that could be estimated using the first few seconds from the initial part of the recording after the arrival of P-waves. From the definition of \( I^{2} \), we can state that:

\[
I^{2} = \int_{t_{p}+T} V^{2}(t) dt = V^{2}_{rms_{p}} T
\]

where the index \( rms_{p} \) indicates the root mean square (rms) value of the velocity estimated from the initial part of P-waves, and \( T \) is the record interval.

The latter expression permits the application of the ideas presented in [48-51], where the rms values of velocity and ground acceleration are related with the source parameters and the attenuation coefficient, using Parseval's theorem, which states that:

\[
y_{rms} = \sqrt{\frac{\int_{-\infty}^{\infty} |y(t)|^{2} dt}{T}} = \sqrt{\frac{\int_{-\infty}^{\infty} |Y(f)|^{2} df}{T}}
\]

where \( y(t) \) is the ground motion time series, \( Y(f) \) is the ground motion spectra, and \( T \) is the record interval.

According to Brune's model [43], the far-field ground motions reads as:

\[
\frac{d^{n}}{dt^{n}} \Omega(f) = (2\pi f)^{n} \frac{M_{0}}{1+(f/f_{0})^{2}}
\]

where \( f \) is the frequency and \( f_{0} \) is the corner frequency. The index \( n = 1,2,3 \) refers to displacement, velocity, or acceleration spectra, respectively. According Brune’s model, the displacement spectra are constant equal to \( \Omega_{0} \) at frequencies well below the \( f_{0} \) and decay as \( f^{-2} \) above it, while the velocity spectra increase proportionally to \( f \) below \( f_{0} \) and decrease as \( f^{-1} \) above it. As equation (2) suggests, the acceleration spectra goes as \( f^{2} \) up to the corner frequency and are flat above it. The spectral parameters \( \Omega_{0} \) and \( f_{0} \) are related to the seismic moment, \( M_{0} \), and the stress drop, \( \Delta \tau \), as follows [52]:
\[ \Omega_o = \frac{M_o U_{\psi \phi}^{PS} F_s}{4 \pi \rho C_s^2 R} \]  

(6)

and

\[ f_o = k C_{ps} \left( \frac{16 M_o}{\pi \rho} \right)^{1/3} \]  

(7)

Where \( U_{\psi \phi}^{PS} \) is the radiation pattern of P and S waves, \( F_s \) is the free-surface correction factor, \( R \) is the hypocentral distance, \( \rho \) is a constant with different values for P and S waves and \( C \) stands for the wave velocity with \( C_p \) and \( C_s \) for the P and S waves, respectively [53, 54]. The expression (7) is valid for a circular crack embedded within an infinite homogeneous isotropic Poissonian medium. The effect of site and path attenuation can be modelled by multiplying the source spectra with an exponent function [55]:

\[ \frac{d^n}{dt^n} \Omega(f) = (2\pi f)^n \frac{M_o}{1 + \left( \frac{f}{f_o} \right)^2} \exp(-\pi \kappa_o f) \]

where \( \kappa_o \) is an attenuation parameter that embodies both anelastic and near surface attenuations. \( \kappa_o > 0 \) results in a high-frequency decay of the spectra and effectively produces an additional corner frequency, \( f_k = 1/(\pi \kappa_o) \).

Using Parseval’s theorem, in [48-51] the displacement, velocity, and acceleration ground motion \( rms \) are obtained as:

\[ \left( \sqrt{\frac{d^n}{dt^n} D} \right)_{rms} = \Omega_o \sqrt{\frac{2}{\pi}} \int_0^\infty (2\pi f)^n \frac{1}{1 + \left( \frac{f}{f_o} \right)^2} \exp(-2\pi \kappa_o f) df \]

(8)

Since the solutions of the integrals express either the \( rms \) of velocity or acceleration, based on the Meijer G-function, and \( Ci \) and \( Si \) (the cosine and the sine integral functions), respectively, we use some approximate expressions that are valid for moderate and strong earthquake events that match the exact solutions for the \( rms \) values of velocity, and acceleration (for details see [48-51]), as follows:

\[ V_{rms_p} = 2\pi \Omega_{op} \sqrt{\frac{\pi f_o^2}{2\pi}} \]

(9)

\[ A_{rms} = (2\pi)^2 \Omega_{os} \int_0^f \frac{1}{\sqrt{\pi \kappa_o}} \]

(10)

The latter expressions suggest that for moderate and strong earthquake magnitudes the \( rms \) of velocity \( V_{rms_p} \) is insensitive to attenuation, while the \( rms \) of acceleration, \( A_{rms} \), depends on the attenuation coefficient \( \kappa_o \).

Combining equations (3), (9) and (10) we obtain:

\[ \log A_{rms} = \frac{1}{2} \log \frac{V_{rms}}{V_p} + \log \left( \frac{2 U_{\psi \phi} R_1}{U_{\psi \phi} R_2} \frac{C_p^3}{C_s^3} \frac{2 f_o}{\sqrt{\pi \kappa_o}} \right) \]

(11)

for the on-site scaling

and

\[ \log A_{rms} = \frac{1}{2} \log V_{rms} + \log \left( \frac{2 U_{\psi \phi} R_1}{U_{\psi \phi} R_2} \frac{C_p^3}{C_s^3} \frac{2 f_o}{\sqrt{\pi \kappa_o}} \right) \]

(12)

for the inter-site scaling

where \( R_1 \) the hypocentral distance of the close to epicenter station where first detected the seismic wave, while \( R_2 \) the hypocentral distance of the target site.
Taking into account that PGA = γAV_{rms}^{\nu} [48-51], where the local site effects, are taking into consideration in the parameters γ and ν, the above expression leads to:

\[ \log \text{PGA} = \frac{\nu}{2} \log I_{P}^{2} + v \log \left( 2 \frac{U_{\phi,0}}{U_{\phi,0}} \right) c_{p}^{3} \frac{\sqrt{2f_{0}}}{\kappa_{s}T} + logy \] (13)

for the on-site scaling

and

\[ \log \text{PGA} = \frac{\nu}{2} \log I_{P}^{2} + v \log \left( 2 \frac{U_{\phi,0}}{U_{\phi,0}} \right) c_{p}^{3} \frac{\sqrt{2f_{0}}}{\kappa_{s}T} + logy \] (14)

for the inter-site scaling.

Expressions (13) and (14) have the form of equation (2) where b=v/2. The latter suggests that when ν = 1, then b ≡ 0.5 as in most of the cases observed [31, 33, 34]. Worth to mentioned that the main advantage of equations (11) to (14) is that based on a simple widely adopted physical source model (attenuated omega-square spectra) could reproduced the empirical formulation of equation (2) which presented in a significant number of observations [see 31, 33 and references therein]. As such, it accounts for the three most important source parameters affecting ground motion intensity; the seismic moment (commonly expressed through the earthquake magnitude), the hypocentral distance, and the stress drop, as suggested by equation (7).

4. Concluding remarks

Today, the development of EEWSs represents one of the most useful strategies to mitigate seismic risk in short timescales, and several countries worldwide are promoting and developing such systems. In the context of seismic risk management, they are considered a reasonably cost-effective solution for loss reduction [56]. In this study, we explored the physical basis of the scaling laws, both on-site and between stations located near the earthquake sources and target sites, in order to estimate inter-site relations for I_{P}^{2} (recorded at the former) and PGA (recorded at the latter). Our results justify the scaling between I_{P}^{2} and PGA at individual sites, with seemingly identical slope parameters. This scaling bears hope for establishing both on-site and inter-site hazard estimators. The physical ground of the scaling between I_{P}^{2} and PGA could be used to improve recent approaches that use I_{P}^{2} parameter to estimate the strength of strong ground motion using modern artificial intelligence techniques as that of machine learning [57-60].

Summarizing, in the present work, on-site and inter-site theoretical scaling relations of the far-field ground motions were derived using the omega-squared model. The scaling laws between I_{P}^{2} and PGA are in agreement with recently observed empirical relations and could be used as earthquake early warning parameter. Further work is required to better support this and solve issues such as the actual consequences of local site effects. However, if these matters are resolved and the robustness of both the empirical and theoretical bases is improved, the on-site and inter-site EEWS approaches could be used to issue alerts and, even, estimate potential damages level within very few seconds, faster than the in-operation regional EEWSs.

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