Theoretical models of seismic electromagnetic radiation based on piezoelectric effects

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To explain the phenomenon of the electromagnetic disturbance that occurs prior to earthquakes, we conducted a theoretical study of the relationship between the characteristics of electromagnetic disturbances before earthquakes and the seismogenic stress field generated by piezoelectric effects. Seismic wave field model of natural seismic excitation was studied from the perspective of the piezoelectric effect, and the electrical model developed described the evolution of the pre-earthquake electromagnetic field coupled with the seismic wave field. The relationship among the electromagnetic radiation intensity, the parameters of the geologic medium and the propagation distance in the coupling was also investigated. One of the main mechanisms underlying electromagnetic anomalies in certain bands during a strong earthquake was the release of an electromagnetic wave generated by the transmission of a stress wave in rock containing piezoelectric crystals. The change in the pre-earthquake electromagnetic field was affected by its interaction with the seismic wave field, the properties of the medium of the observation points and the distance from the epicentre. Present study suggest that to avoid great uncertainty, analyses of seismic observations should be combined with background information, including a comparison between electrical measurement results and geophysical data.

[Key words: piezoelectric effect, earthquake electromagnetic field, seismic wave, earthquake]

Introduction

It has been known for decades that electromagnetic phenomena can often be detected before a strong earthquake. These abnormal electromagnetic wave signals produced before an earthquake were thought to be associated with rock deformation and fracture; therefore, scholars have performed numerous studies of the electromagnetic radiation emitted during the process of rock deformation and fracture1,2&3. Warwick proposed the piezoelectric model of seismic electromagnetic radiation, and Davis et al. explained the magnetic field variations prior to earthquakes in terms of piezoelectric effects, both of which are radiation mechanisms caused by stress. Advancements have been achieved in summarising the characteristics of electromagnetic radiation and developing theoretical models based on piezoelectric effects to study the mechanism of abnormal electromagnetic signals before and during earthquakes4&5. Warwick et al. proposed piezoelectricity as the source of the electromagnetic phenomena observed in the 1960 Chile earthquake6. The experiment on granite conducted by Yoshida et al. showed that the electric field strength is linearly and positively correlated with the stress rate. This group further compared the experimental results from granite with those from non-piezoelectric rock and confirmed that piezoelectricity is the most important mechanism leading to electromagnetic signals during rock ruptures7. Ogawa et al. assumed that new surfaces appear during rock rupture and that the bilateral walls of the rupture possess positive and negative charges, thus functioning as a doublet to charge and discharge and creating outwardly radiating electromagnetic signals8. Cress et al. assumed that gallets are produced during rock rupture and that electrostatic charge is distributed on the surface of these gallets; furthermore, the vibration, rotation and rectilinear motion of these gallets are the major reasons for the generation of low-frequency electromagnetic radiation, whereas the high field caused by the charge separation on the rupture surface causes air breakdown, leading to high-frequency electromagnetic radiation9. Although Brady et al. also assumed that the piezoelectric effect does not greatly contribute to photo-radiation, they confirmed the roles played by rock using
piezoelectric crystals, the emitted electromagnetic waves within certain frequency ranges of which are more powerful than those from rock that does not contain piezoelectric crystals\(^\text{10}\). All of these aforementioned studies support the assumption that the piezoelectric effect causes convective discharge, but the contribution of piezoelectric crystals in rock to the generation of electromagnetic waves has not yet been quantified.

To explore the mechanisms underlying electromagnetic radiation during the dynamic process of rock rupture as well as the inherent connections among the mechanisms involved, scholars have researched the possible mechanisms via model establishment and analogue computation\(^\text{11,12,13&14}\). Ogawa et al. summarised and analysed the basic characteristics and detectability of seismic electromagnetic signals based on the piezoelectric characteristics of geological bodies\(^\text{15}\). Koshevaya et al. conducted a theoretical study with a simulation of seismic electromagnetic phenomena based on the piezoelectric characteristics of rock, and their obtained frequency spectra showed good agreement with the electromagnetic radiation frequencies observed during volcanic eruptions and earthquakes, which strongly validated their proposed theoretical model\(^\text{16}\).

Despite the achievements of these studies on the electromagnetic radiation during rock rupture based on rock piezoelectricity, studies of the electromagnetic radiation generated by rock under different forms of stress waves, particularly degenerative stress waves, are lacking. The quantitative relation between the electric field intensity value of the electromagnetic field and the strain are particularly ripe for further exploration.

In the present study, based on the fact that many rocks contain substances with a piezoelectric crystal structure, we studied the electromagnetic generation and transmission mechanisms associated with rock deformation and rupture using the theory of simultaneous inter-coupling of stress waves and electromagnetic waves in quartz-containing rock types from the perspective of wave fluctuation. The aim of this study was to reveal the relations between different stress wave amplitudes and frequencies as well as the intensity of the radiated electromagnetic waves, and satisfactory results were obtained.

### Materials and Methods

**Electromagnetic radiation generated by seismic waves:**

In earthquake studies, seismic sources are often described with single-point force sources or electric dipole fields. Aki and Richards described a source of seismic wave fields excited by single-point force sources in elastic media. Due to the changes in the electric field of the geological body before the earthquake, the natural physical source, the force source and the dipole field are combined to represent the natural seismic source. By integrating the common effects of geometric attenuation and physical attenuation and considering a spherical stress wave originating from a point source (Yoshida et al. 1994), the following formula is obtained:

\[
T = T_0 e^{-\eta r} / r \quad (1)
\]

In this formula, \(\eta\) is the decay rate and \(r\) is the seismic source radius.

The following discussion focuses on a dipole field in a homogeneous infinite medium. The surface of the earth is negatively charged by approximately 500,000 C. Under normal circumstances, the interior of the earth is neutrally charged. When an earthquake occurs, the fracture and fault slip in the rock cause the radiation of electromagnetic waves. The process of expansion and dilation indicates that liquid flow causes the positive and negative charges on the two-phase interface to separate and flow. The charge flow in the liquid in the gap of the expansion area forms an even electric body with positive and negative changes in the seismogenic zone on which the total charge is zero; this event can be described by a characteristic quantity known as the total dipole moment, \(P\), which is defined as follows:

\[
p = \iiint \rho(v',u',w',t)r'dV \quad (2)
\]

In this formula, \(\rho(v',u',w',t)\) is the current density at the moment \(t\) of \((v',u',w')\) and \(r'\) is the radius vector from the origin to \((v',u',w')\). Integral is taken over the region in which the net charge is non-zero. Generally speaking, the types of electromagnetic field changes can be categorised as quasi-static, induction field and radiation field. The compositions of the electromagnetic fields vary with the distance from the source and the frequency of measurement. For harmonic field conditions, the relationship between \(\varphi\) and \(\zeta\) is obtained using the Lorenz
condition formula:
\[
\phi = -\frac{i\omega}{k^2} \nabla \zeta
\]  

(3)

According to Maxwell’s equations, the relationship between the potentials of the electric and electromagnetic field is described as follows:
\[
E = -\nabla \phi - \frac{\partial \zeta}{\partial t}
\]  

(4)

In this formula, Φ and ζ represent the scalar potential and vector potential of the electromagnetic field, respectively. The midpoint of the dipole is taken as the origin, the dipole axis is taken as the Z-axis, Q is any point in space and \( O \) and \( O_1 \) indicate the equal and opposite charges on the ends of the electric dipole. The changes in these charges can be expressed as \( \Phi_1 = \Phi_0 e^{i\omega t} \) and \( \Phi_2 = \Phi_0 e^{-i\omega t} \).

The dipole moment is described as follows:
\[
\delta_M = \Phi_1 = \Phi_0 e^{i\omega t} = -\frac{i j_0}{\omega}
\]  

(5)

The electric dipole potential is described in equation (6):
\[
\zeta = \frac{\mu e^{-i\omega t}}{4\pi} \int_{-1/2}^{1/2} \frac{e^{ikr}}{r} \, dl
\]  

(6)

where \( \mu = \frac{\mu_0 d z T_0 \omega^2}{\eta^3 + i 2 k \eta + \mu_0 \epsilon_{\infty} \omega^2 - k^2} \), \( \eta \) is a constant, \( c_0 = a / r + b \), \( \mu_0 \) is the permeability of the vacuum, \( j_c \) is the conduction current density and \( \epsilon_{\infty} \) is the dielectric constant.

\[
E_x = i\omega \zeta_0 + \frac{1}{k} \frac{\partial}{\partial \theta} (\nabla \zeta) - \frac{i\omega j_0}{2k} \frac{1}{r} \frac{\partial}{\partial r} r e^{i(kr - \omega t)} \cos \theta
\]

\[
E_y = i\omega \zeta_0 + \frac{1}{k} \frac{\partial}{\partial \theta} (\nabla \zeta) - \frac{i\omega j_0}{2k} \frac{1}{r} \frac{\partial}{\partial r} r e^{i(kr - \omega t)} \sin \theta
\]

\[
E_z = 0
\]

(7)

Thus far, we have described all of the components of the electric field produced by an electric dipole in an infinite medium.

In the near field, \( kr << 1 \), and the component of the electric field that is non-zero can be written as follows:

\[
E_r = \frac{i\omega j_0}{2\pi} \frac{e^{-i\omega t}}{r^3} \cos \theta
\]

(8)

\[
E_\theta = \frac{i\omega j_0}{2\pi} \frac{e^{-i\omega t}}{r^3} \sin \theta
\]

In the far field, \( kr >> 1 \), and the component of the electric field that is non-zero can be written as follows:

\[
E_r \approx -i\omega j_0 \mu_0 \frac{\cos \theta}{2\pi r} e^{i(kv - \omega t)}
\]

(9)

Because \( E_r \) is much smaller than \( E_\theta \), the electromagnetic field in the far field transforms into a transverse electromagnetic wave travelling along the \( r \) direction.

Therefore, a seismoelectric wave field excited by an earthquake source in a homogeneous medium is derived based on the piezoelectric effect together with consideration of the interaction between a point source and an electric dipole source.

Coupling of a seismic wave and an electromagnetic wave:

Over time, the change in the seismic wave field will cause a change in the electromagnetic field. In nature, rock is mostly composed of piezoelectric material. The stress wave and electromagnetic wave may be coupled, and in this work, we consider the delay effect (i.e., we did not adopt the static electricity and static approximation) to examine the electromagnetic wave phenomena that occur during the propagation of the stress wave in the piezoelectric rock.

The relationship between an electromagnetic wave and an incident seismic wave is determined based on the piezoelectric constitutive equations. The electromagnetic radiation emitted from the rock under the effect of a longitudinal wave is described as follows:

Assume that a V-wave is a propagating polarised longitudinal wave of \( v \).

\[
T_1 = v T_0 e^{-\alpha v} e^{i(\omega t - kr)}
\]

(10)

In this formula, \( \omega \) is the frequency of the seismic wave. According to the piezoelectric constitutive equation, the seismic wave field induces a piezoelectric response to the potential displacement:
\[ D_w = d_{wT_1} \tag{11} \]

and a flexible response to the seismic wave field \( G \), \( (d_{wT_1}) \) occurs. When a piezoelectric \((D_w)\) is introduced into the electromagnetic equations, it produces a magnetic field and an electric field, which must be used to calculate the dispersion relation of the plane waves. The fluctuating electromagnetic field variables obey Maxwell’s equations:

\[
\nabla \times E = -\frac{\partial B}{\partial t} \tag{12} \\
\nabla \times H = -\frac{\partial D}{\partial t} + J_c \\
B = \mu_0 H
\tag{14} \\
\]

In these formulae, \( B \) is the magnetic induction, \( H \) is the magnetic field strength and \( D \) is the potential vector. If equations (10) and (11) are introduced into Maxwell’s equations, the result is the following:

\[
\frac{\partial^2 E_x}{\partial t^2} - 2k \frac{\partial E_x}{\partial r} + (\mu \varepsilon_0 \omega - k^2)E_x = -\mu_0 \mu_0 \omega \varepsilon r / r \tag{15} \\
\]

Solving the differential equation yields the following:

\[
E_e = (c_i \varepsilon^{(k + w \mu \varepsilon_0) r} + c_1 \varepsilon^{(k - w \mu \varepsilon_0) r} + c_3 \varepsilon^{-w r}) \tag{16} \\
\]

Suppose that a w-polarisation occurs in a medium; if the particle displacement of the w-propagation (longitudinal) is \( u = w \cos(\omega t - k \cdot r) \) and the seismic wave field associated with this displacement is \( G = \frac{\partial u}{\partial w} \), the following formula is obtained:

\[
E_x = \frac{\mu_0}{\mu \varepsilon_0 \omega - k^2} \sin(\omega t - k \cdot r) = -\frac{\mu_0 \varepsilon_0 \omega}{k} G_s \tag{17} \\
\]

Suppose that the Sr wave of the w-polarisation and the particle displacement of the v-propagation are described as \( u_w = w \cos(\omega t - k \cdot r) \) and \( G_s = \frac{\partial u_w}{\partial v} = k \sin(\omega t - k \cdot r) \), respectively; then, the following formula is obtained:

\[
E_v = -\frac{\varepsilon_{sv}}{\varepsilon_{sv}} G_s \tag{18} \\
\]

The following coupled equations are subsequently obtained:

\[
E_x + E_v = -\left(\frac{\mu_0}{\mu \varepsilon_0 \omega - k^2} + \frac{\varepsilon_{sv}}{\varepsilon_{sv}} k\right) \sin(\omega t - k \cdot r) \tag{19} \\
\]

From the above formula, the electric field is observed as correlated proportionally with the seismic wave field. Accounting for attenuation in the process of the radiation signal propagation in the formula using \( e^{-w t} \), the above formula is transformed into the following:

\[
E = -(\frac{\mu_0}{\mu_0 \varepsilon_0 \omega^2 - k^2} + \frac{\varepsilon_{sv}}{\varepsilon_{sv}} k) \sin(\omega t - k \cdot r) e^{-\eta t} \tag{21} \\
\]

where \( \eta \) is the attenuation coefficient, \( \beta \) is the electrical resistivity, \( \varepsilon \) is the dielectric constant, \( \sigma \) is the conductivity and \( \mu_0 \) is the magnetic permeability. The attenuation coefficient can be expressed as follows:

\[
\eta = \frac{\omega \sqrt{\mu_0 [\sqrt{\varepsilon^2 + (1 / \omega \beta)^2} - \varepsilon]}} {22} \\
\]

Introducing the attenuation coefficient into the above formula, we obtain the following:

\[
E = -(\frac{\mu_0}{\mu_0 \varepsilon_0 \omega^2 - k^2} + \frac{\varepsilon_{sv}}{\varepsilon_{sv}} k) \sin(\omega t - k \cdot r) e^{-\eta t \left(22 \frac{\mu_0}{\mu_0 \varepsilon_0 \omega^2 - k^2} + \frac{\varepsilon_{sv}}{\varepsilon_{sv}} k\right)} \tag{23} \\
\]

The formula above describes the relationship between the electrical parameters of the electric field and the motion of the geological body.

**Parameter selection:**

The full transient analysis method is applied to perform the numerical calculations based on the model described above. The gravity of the geological body is not considered. The case considered in the calculation assumes that the properties of both sides of the joint surface of rock are the same and that the earthquake magnitude is in the range of 5-7. The largest extensive degree of the source is determined by a source size of \( d \approx 10^3 \) m, the current density is \( j_0 = 1-10 \) A/m², the permeability is \( \mu_0 = 1.2 \times 10^{-6} \) Hm⁻¹, the dielectric constant is \( \varepsilon_{sv} = 1.2 \times 10^{-11} \) Fm⁻¹, the piezoelectric coefficient is \( \varepsilon_{sv} = -0.051 \) C/m² and the frequency is \( f = 1 \) Hz. The elastic modulus of both the surface-covering layer and the bedrock is taken as \( E = 30-100 \) (GPa) in the calculation, and the Poisson ratio is 0.25. The numerical simulation of the geological body is conducted throughout the entire process from
earthquake initiation to the appearance of the electromagnetic radiation.

**Results**

Theoretically, the changes in the electromagnetic radiation intensity caused by changes in a single parameter are clear, but the collective influence of multiple parameters renders the intensity changes in the electromagnetic radiation highly complex; therefore, the quantitative study in this work primarily focuses on the changes in the intensity of the electromagnetic radiation influenced by the focal distance and electrical parameters such as the piezoelectric coefficient and the resistivity. Resistivity is an important factor affecting the electromagnetic radiation intensity (Figs. 1, 2 & 3). The greater the increase in resistance, the greater the increase in the intensity of the electromagnetic wave. The effect of geo-electrical resistivity must be considered at observation points of different distances. In addition, the closer the monitoring point is located to the centre of the seismic source, the larger the amplitude of the monitored electromagnetic radiation and the amplitude attenuates with the increase in the propagation distance. Due to the discontinuity of the geological bodies, the wave field attenuates during propagation. When the pressure of propagation distance reaches 100 km, the electromagnetic radiation energy decreases to nearly 0, and the electromagnetic anomaly can be observed. According to this calculation, the resistivity of the geology should be relatively high, for example, greater than 2000 ohm/M. The transmission distance of the electromagnetic radiation information is influenced by the signal frequency and the electric parameters of the rock masses (resistivity).

The impedance is proportional to the elastic modulus; therefore, the elastic modulus is another important factor that influences the electromagnetic radiation intensity. The larger the elastic modulus, the higher the intensity of the electromagnetic radiation. The changes in the electromagnetic radiation amplitude caused by the elastic modulus are relatively large, which demonstrates the influence of the electrical parameters of the geological body on the amplitude of the emitted electromagnetic radiation. Experimental results indicate that when the rock is close to its breaking point, the electromagnetic radiation intensity and frequency range are closely related to the physical properties of the geological body. For different geological bodies, the electromagnetic radiation is affected by the elastic modulus and the resistivity (Fig. 4), which is consistent with the observations. The theoretical results in this paper provide both theoretical support to the observed electromagnetic characteristics and ideas for future observational methods. According to the field observations, the duration of the electromagnetic anomaly is from

![Fig. 1-Wave field of electromagnetic radiation during an earthquake](image1)

![Fig. 2-Waveform of an electric field](image2)

![Fig. 3-Changes in electromagnetic radiation amplitude with propagation distance for different resistivity values](image3)
several minutes to a few hours. The results in this paper show that within a few minutes, the electromagnetic anomaly has decayed to zero, which is consistent with field observations, but there are no observations showing that variations of mechanical parameters on such time scales exist in the process of an earthquake. Further research on the seismogenic process as a function of time is necessary.

Fig. 4-Changes in electromagnetic radiation amplitude with time for different elastic moduli

Discussion

Thus far, no quantitative estimates have been produced for the contribution of piezoelectric crystal to the production of electromagnetic wave in seismic rock. From the perspective of the piezoelectric effect mechanism, this paper adopts numerical simulation to systematically study the electromagnetic radiation in rock generated by stress waves. This work also contributes to the research on electromagnetic radiation generated by force waves of various forms and the coupling behaviour between stress waves and electromagnetic waves in different crystal structures. This paper describes the electromagnetic radiation characteristics of the coupling between seismic waves and the electromagnetic waves based on the piezoelectric effect. The coupling process between the seismic wave and the electromagnetic wave during the pre-earthquake period is also studied theoretically, and a preliminary qualitative research study on the seismic electromagnetic radiation is performed using the proposed electrical model. This work also provides both semi-quantitative and semi-qualitative explanations for a number of phenomena that have been observed during electromagnetic monitoring. The relationship between the electromagnetic radiation characteristics during the process of an earthquake and the seismic wave field is described, and the results can aid in explaining the electromagnetic disturbances that occur during a seismogenic process.

a. In a rock mass containing a quartz isobaric transistor, stress wave propagation was also accompanied by the propagation of electromagnetic waves, and the amplitude of the two waves was proportional; in other words, strong stress waves co-occur with strong electromagnetic phenomena in the same frequency range. Quantitative estimates for the contribution of piezoelectric crystals to the production of electromagnetic waves in seismic rock is still lacking, but this research result is consistent with the results of previous experiments and electromagnetic anomalies observed during earthquakes.

b. As previous researchers have observed, the electromagnetic anomalies and luminescence that occur before strong earthquakes are comprehensively affected by different types of mechanisms\textsuperscript{17}. According to the analysis results of the present paper, electromagnetic phenomena in selected frequency bands are enhanced in rock masses that contain a piezoelectric crystal structure. Therefore, one of the main mechanisms that drive electromagnetic anomalies in certain bands during strong earthquake is the release of electromagnetic waves generated by the transmission of a stress wave in piezoelectric crystal rock. Electromagnetic anomaly records from several earthquakes also indicate that prior to an earthquake, the electromagnetic radiation in selected bands is exceptionally strong\textsuperscript{17}. From the geological conditions of the earthquake areas where the phenomena have been recorded, most of the electromagnetic anomalies occur in regions that display a high content of crystals such as quartz in the rock\textsuperscript{18}. These results confirm our theoretical results.

This paper discusses the mechanism of seismic electromagnetic radiation and certain results. However, the earthquake mechanism is complex, and many influential factors exist. Indeed, the conductivity of mantle minerals and rocks is affected by many external factors and internal factors. Each factor is likely to lead to different conductivities, and such differences can reach several orders of magnitude. Therefore, in the study of electrical conductivity, it is necessary to consider the thermodynamic conditions and internal factors together with accurate
quantification, and subsequently, comparisons of conductivity measurements and geophysical data can be made available; otherwise, great uncertainty will remain.

The electromagnetic phenomena observed in rock experiments and in practical examples of earthquakes demonstrate both similarities and contradictions. Therefore, research on electromagnetic radiation in rock requires broader and deeper experimental studies as follows:

a. Additional electromagnetic radiation data should be acquired from the development and occurrence processes in seismic disasters. The performance of the precursor earthquake electromagnetic information identification model should be fully verified.

b. In addition to the relationships among the different influencing factors of conductivity, other factors that affect the conductivity should be examined. Using the quantitative relationship obtained from the laboratory between conductivity and certain factors (temperature, oxygen fugacity, iron content, water content), the global or regional distribution of factors that are important to account for in the interior earth can be identified.

c. The magnitude of the piezoelectric effect is not high; therefore, it is difficult to explain all of the abnormal phenomena of the electromagnetic field. The internal connections among the mechanisms that generate electromagnetic radiation during an earthquake require further study.

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