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Effect of Variation of the Coefficient of Friction on the Temperature at the Level of the Fault Lips

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Abstract

Earth's crust is an anisotropic and purely heterogeneous medium, which is justified by existence of different discontinuities; our study aims to show the effect of the variation of coefficient of friction on the evolution of temperature and its impact on seismic forecasting. In this work, we are model in 2D the variation of thermal energy and temperature produced by friction at the level of fault lip as function of depth of the seismic focus and at different value of time. Earthquakes are born when the energy accumulated by friction at the level of fault is suddenly released causing damage, sometimes noticeable on the surface of earth (macroseisms), and sometimes not at all noticeable on the surface of earth (microseisms), then energy which occurs before is important to forecasting earthquake. Assuming that coefficient of friction is variable, our results have enabled us to highlight the fact that, the greater the coefficient of friction, more the temperature increases, although the temperature profile increase over time but not linearly reflecting the presence of different asperities and discontinuities zone; slip generated at the level of fault occur a variation of temperature on specific points called roughness in common agreement with the literature. A large part of energy produced by friction is dissipated in heat causing a local increases in temperature which a very short duration and called flash contact temperature, and that despite the fact that the temperature evolved in time and space, it all converged towards a perfectly distinguishable fixed point.

Keywords

Earthquakes, Coefficient of Friction, Nucleation Phase, Temperature Variation, Energy Variation, Asperity Point

1. Plain Language Summary

In this draft article, we model the thermal energy as well as the variation of the temperature produced by friction at the level of the fault lip by admitting the variation of coefficient of friction. The results we obtained are interesting. We have shown in this work that: The slip generated at the level of the fault induces a variation in temperature at specific points called asperities. Beyond a certain value of the depth of the seismic focus, the variation of the temperature produced by friction is null. Temperature and energy profiles obtained following the variation of the friction coefficient reveals heterogeneous character of earth's crust, and there is always an inter-seismic phase (transient phase) between two consecutive seismic events.

2. Introduction

Earthquakes are the result of the sudden release of energy accumulated by friction at the level of fault lip. Generally, the amount of this energy dissipated during earthquakes is unknown [1], but some indirect estimates suggest that frictional losses may constitute a significant part of the earthquake's energy budget [2] [3] [4]. Thermal perturbations associated with seismic slip-on faults may significantly affect the dynamic of friction and the mechanical energy release during earthquakes [1]. Before earthquakes, we observe more anomaly in area of earth like a deformation of rocks allows accumulation of stress energy [5] [6] [7]. According to numerous studies [8] [9] [10] [11], the temperature felt generated on the fault surface is responsible to a large number of physical [12] [13] [14] and chemical dissipation process [15] [16] [17] and by consequence frictional heat on a sliding interface. Mair and Marone [18] observe a dramatic weakening effect or reduced of heat production occur during dynamic slip. With the same idea, [19] [20] observed high magnetic susceptibility and low inorganic carbon content in the principal slip zone of the Taiwan Chelungpu Fault and concluded that, this may result from the formation of magnetic minerals from paramagnetic minerals [21], and thermal decomposition of carbonate minerals respectively [20] before earthquakes. Few years ago, [22] observed a relatively low content of clay minerals in the Chelungpu Fault and suggested that this was due to frictional heating during an earthquake, thus highlighting the effect of increased heat at the level of the fault on the structure of the surrounding rock blocks. According for a last earthquake, more studies and more authors prove that we observe variation of temperature before earthquakes. Sibson [23] and Lachenbruch [24] admitted that coseismic temperature increases can affect the frictional properties of rocks in the fault zone, and also the dynamic stress drops during earthquakes. Li *et al.* [25] show that, before the earthquakes, we also observe a temperature anomaly which systematically affects the morphology of the environment. Most studies of stick-slip friction focus on dynamic motion during slip because of its importance in the evolution of vibration, heat, wear, and in some cases seismic radiation [26]. During the preseismic phase (that is during the nucleation phase), an increase in temperature is generally observed with the displacement at the level of the fault. Studies make it possible to model this temperature today [6] [7]. Schotz [4] is one of the first to assess the energy balance at the level of the fault, he admitted that, this energy is equal to a sum of the energy or of the heat released in the form of seismic waves, of the work produced by friction of the fault surfaces and in the main slip zone and also the work of the gravity forces. Mair and Marone [18] showed that temperature variations at the fault systematically increased frictional shear and velocity; thus, showing the effect of temperature variation on the state of the system. Konga *et al.*, [6] modelled this energy using the first law of thermodynamics; and in 2019, Konga *et al.* [7] modelled again this energy for different laws of friction and also taking into account the influence of viscosity. Their studies enabled them to obtain that the temperature distribution decreases when one moves away from the main sliding zone. Angisboust *et al.*, [27] studied on the basis of thermo-mechanical processes, the importance of fluid circulation on tectonic subduction processes. During this study, the authors proved that the circulation of the fluid along the interface of subduction is at the origin of the discontinuous mafic crust. Nielsen *et al.* [28] investigated the effect of frictional melting on seismic slip processes. Noda *et al.* [11] studied the rupture dynamics of seismic faults taking into account the thermal weakening occurring in a fault. It emerged that thermal pressurization was more important in determining the average working stress in failures with larger amounts of slip than those modelled in their work. Hu and Sun [29] studied the effect of high temperature as well as high pressure on the friction coefficient of rock. They thus demonstrated that in general, the value of the frictional coefficient increases when the value of the temperature increases.

All its authors modelled the thermal energy and the temperature generated by friction at the level of the fault assuming that the frictional coefficient was constant. However, they concluded at the end of their work that the increase in the value of the energy as well as the value of the temperature modified the mineralogical composition of the rock, the structure of the fault and as well as the stress at the level of the fault (therefore the coefficient of friction). However, given its internal structure and the diversity of its composition, several authors [30] [31] have shown that the earth's crust is a heterogeneous medium. It is for this reason that, according to some works in the literature [32] [33], one of the difficulties encountered in the prediction of earthquakes is due to the number of hypotheses that are accepted during their modelling in the laboratory. These assumptions range from rock composition to fault geometry. Thus, according to his studies, we can no longer continue to admit that the coefficient of friction is constant in time and in space throughout the propagation of the seismic wave.

Taking into account all the above, we propose to model the temperature as well as the energy produced by friction at the level of the fault lip by taking into account the temporal variation of the frictional coefficient. To carry out our objective, we will start from a 2D model of the dynamics of an earthquake, in which we will introduce a temporal variation of the frictional coefficient. Then, with the fourth order of Runge-Kutta algorithm, we will bring out the numerical representations of the temperature and the energy. And by a comparative study, we will highlight the effect of the variation of the frictional coefficient on the evolution of the temperature as well as on the evolution of the seismic energy produced by friction at the level of the fault lip. In end through our model, we will try to explain certain phenomena that are observed in reality during the propagation of seismic waves.

3. Description

Earthquakes arise when the energy accumulated by deformations at the level of the fault (main slip zone) is suddenly released. The magnitude as well as the amplitude of the earthquake are strongly linked to this energy. Mathematical relations linking this energy to the seismic magnitude, as well as to its amplitude allow its direct evaluation after the seismic manifestation. However, many processes based on inverse methods make it possible to evaluate this energy at the origin of earthquakes. A large number of works [1] [4] and [34] have shown that there were several forms of energy in the main sliding zone, the most important of which was the energy accumulated by friction at the level of the fault. To this end, [4] and [1] have established that the energy balance in the fault is given by the relationship:

$$W_f = Q + E_s + U_s + W_g \tag{1}$$

According to authors and literature, Q is the heat, E_s is the energy reloaded as seismic waves, U_s is the work of the fault surfaces, W_g is the work of the gravity forces, and W_f is the work of the forces existing in the fault, including friction and ductile deformation. According to its study [35] [36] [37] shows that E_s are negligible compared to the total energy released by an earthquake; U_s is also neglected according to [4] and $W_g \approx 0$. Taking all this approximation, Equation (1) become:

$$W_f = Q \tag{2}$$

This relation Equation (2) proves that most of the energy produced at the level of the fault is equivalent only to the work of frictional forces and deformations which exist in the fault [1]. This work of frictional forces is defined mathematically by the relation below:

$$Q(x,y,t) = \begin{cases} -\dfrac{\boldsymbol{F}\cdot\boldsymbol{v}}{\theta} & \text{if } -h \le \theta \le h \\ 0 & \text{if } \theta \ge h \end{cases} \tag{3}$$

In this relation, $\boldsymbol{F}$ is a frictional force as level of fault, $\boldsymbol{v}$ is the vector velocity of the block defined by the relation Equation (4b), h and θ is a volume of spring block. Note that the work generated by the friction $Q(x,y,z,t)$ at the level of fault is in reality equal to the work of force necessary to move the spring as a whole on the plane (x,y). This work done is not depend directly to component x, y but she depends of time during in which the movement take place.

The friction force was defined by [38] in 2D taking into account the friction function Equation (4a).

$$F = F_0 \phi\left(\frac{v_r}{v_f}\right) = F_0 \phi\left(2\gamma_c v_r\right) \quad (4a)$$

$$v = \sqrt{\dot{x}^2 + \dot{y}^2} \quad (4b)$$

$$\phi(x) = \begin{cases} \frac{1}{1+x} & \text{if } 0 \le x \le 1 \\ 0 & \text{if } x \ge 1 \end{cases} \quad (4c)$$

where F_0 represented the statistical friction force, γ_c is constant coefficient of friction, and ϕ is the function of friction define by Equation (4c). The speed defined by the relation Equation (4b) is the solution of the differential Equation (5) translating the 2D dynamics of an earthquake, introduced and defined by [39] by:

$$\begin{cases} \ddot{x} = -kx + \phi\left(2\gamma_c v_r\right)\cos\left(\varphi_{fr}\right) \\ \ddot{y} = -y + \phi\left(2\gamma_c v_r\right)\sin\left(\varphi_{fr}\right) \end{cases} \quad (5)$$

Where $\varphi_{fr} = \pi + \varphi_{el} - \left(\varphi_{el} - \varphi_{vr}\right)\left[1 - \exp\left(-\Omega v_r\right)\right]$, is the angle who giving the direction of friction force with tectonic plaque; k anisotropy parameter. And $v_r = \sqrt{\left(\dot{x} - v_x\right)^2 + \left(\dot{y} - v_y\right)^2}$ is relative velocity of the slider with respect to the surface [38]; with v_x and v_y are the velocity components of the tectonic plate v_0 (see **Figure 1**).

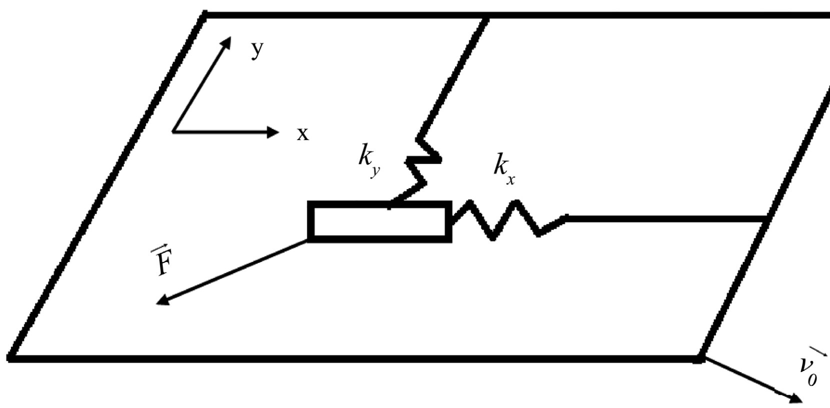


Figure 1. 2D model of block M.

4. Influence of Coefficient of Friction

By definition, the coefficient of friction is the response of a couple of materials to an external stress in a given environment. It is generally a function of localized adhesive force at the points of true contact [40]. Several factors can influence frictional coefficient, namely: the mechanical properties of materials, the surface parameters or even the environmental parameters, the roughness, the sliding speed or the temperature [40] [41] a part; and on the other hand, it is dependent on the real contact surface and not on the macroscopic contact [42] [43]. In their work, the authors report that the surface actually involved in friction presents a microscopic roughness and it is the sum of the microscopic contacts which constitutes the real contact. However, in addition to the works of [42] [43], other works in the literature have also shown that the coefficient of friction at the macroscopic scale integrates the distribution of heights, the geometry of asperities and the local behavior at the level of each contact.

Generally, the friction between two surfaces of large section is always modeled by a statistical approach, not taking into account the elementary contribution of each contact between antagonistic roughness's [40] [41]. Yet, the seismic wave does not always propagate uniformly in time as proven by many works in the literature. Moreover, knowing that the propagation of the seismic wave induces disturbances in the temperature of the incident medium and that, the coefficient of friction is sensitive to the variation in temperature, it will be assumed that frictional coefficient is linked to the vibration frequency of the seismic wave and time by the relation Equation (6). Considering the fact that the earth's crust is heterogeneous, which is justified by the existence of different discontinuities and taking account of all the above, we will admit a temporal variation of frictional coefficient by analogy to the work of [44]. Moreover, according to the work of [40] [41], it is known that the coefficient of friction is a relatively unstable. Thus, we will admit in the following that the coefficient of friction γ is a function of time and defined by the relation by:

$$\gamma(t) = \gamma_c + \delta_\gamma \sin(\omega t) \tag{6}$$

In relation Equation (6), γ_c is constant coefficient of friction, δ_γ is a characteristic parameter of the medium, and $\omega = 2\pi f$ is the pulsation and is characterized by the vibrational frequencies *f* of the system, and δ_γ are characteristic constants of the system. In order to have the effect of the temporal variation of the coefficient of friction on the evolution of our system, we will act on the value of the pulsation ω.

According to Fourier law and the first principle of thermodynamics in the presence of an internal heat source, the energy balance of the system is given by:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho C_p}\frac{\partial^2 T}{\partial z^2} + \frac{Q(t)}{\rho C_p} \tag{7}$$

where $Q(t)$ is a rate of frictional heat generation within the slipping zone [1] and define by relation Equation (3); λ, ρ and C_p represent respectively, the thermal conductivity of the medium, the volume mass of the medium and thermal capacity at constant pressure.

5. Numerical Simulation and Analysis

In the rest of our work, we will dimension the equation Equation (7). For that, we're consider the new dimensioned variable z^* and t^* define by: $t^* = \alpha t / H^2$ (which corresponding to $\Delta t^* = \alpha \cdot \Delta t / H^2$, which is the rate of temperature change due to fault slip in the plane (x, y)) and $z^* = z/H$ (with *H*, which corresponds to the depth of the fault and, $\alpha = \lambda / \rho C_p$ is the heat diffusivity of medium. Taking into account its new dimensioned value z^* and t^* in Equation (7), a new dimension-valued equation is obtained; and after that if we go back to the original variable with *z* and *t*, Equation (7) become:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} + \frac{Q \cdot H^2}{\rho C_p} \tag{8}$$

To solve the Equation (8), we discretize it and we get the new equation described by relation (9):

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = \alpha \frac{T_{i+1}^{n+1} + T_{i-1}^{n+1} - 2T_i^{n+1}}{\Delta z^2} + \frac{Q_i^{n+1} H^2}{\rho C_p} \tag{9}$$

From this discretization, if we admit that T_i^n is the value of the temperature at a given instant and that T_i^{n+1} is its value at a later instant, then the solution T_i^{n+1} of the Equation (9) is given by conjecture by the relation:

$$\left(\frac{1}{\Delta t} + \frac{2\alpha}{\Delta z^2} \right) T_i^{n+1} = \frac{\alpha}{\Delta z^2} \left(T_{i+1}^{n+1} + T_{i-1}^{n+1} \right) + \frac{T_i^n}{\Delta t} + \frac{Q_i^{n+1} H^2}{\rho C_p} \tag{10a}$$

with initial conditions:

$$\text{For } z = 0, \; -\lambda \left. \frac{\partial T}{\partial z} \right|_{z=0} = 0 \text{ and for } z = L, \; T = T_{initial} \tag{10b}$$

The particular cases $\omega * t = \varepsilon \pi / 2$ with $\varepsilon \in \mathbb{Z}$ will not be the subject of our analysis, because for such a value $\sin(\varepsilon \pi / 2) = \pm 1$ and we'll come back just in case $\gamma = cste$ which have already been the subject of several studies. However, a particular for $\omega = 0$ will be the subject of a brief analysis in order to compare our results with some found in the literature. By comparing the figures obtained for $\omega = 0$ (**Figure 2**) to that obtained by [45], we see that we almost have the same shapes of curves. The noticeable differences between the two can be justified by the difference in parameter value on the one hand and by the difference between the two models. Indeed, in this work the author using the 1D dynamics of an earthquake, to studies the effect of the temporal variation of the intrinsic parameters a and b on the dynamics of an earthquake, while here we are using a 2D model of the earthquake.

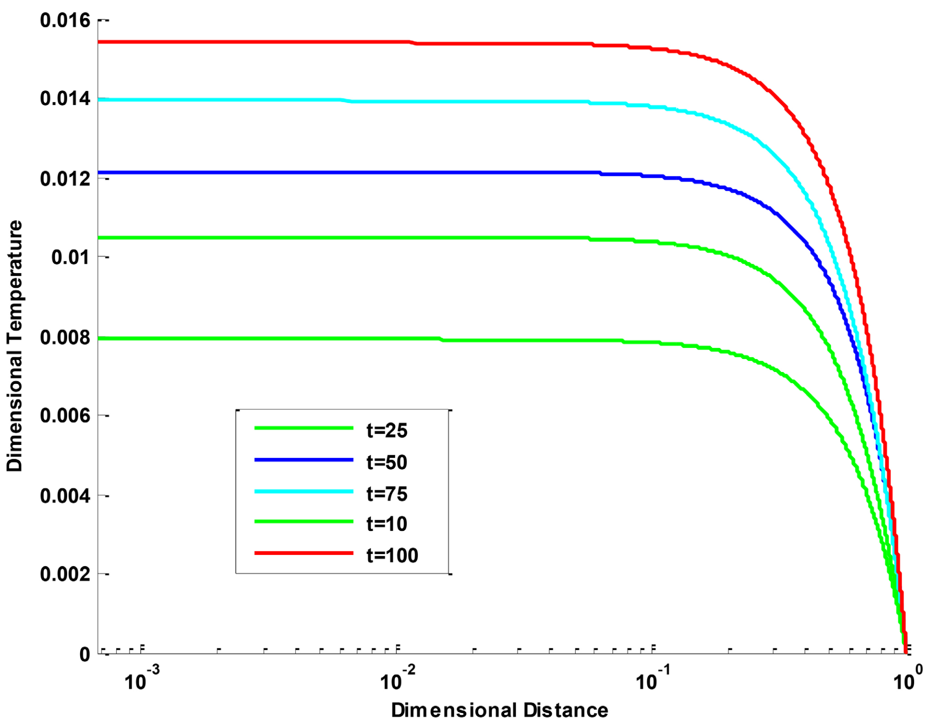
Assuming that frictional shear τ is written in the form of $\tau = \mu \sigma$, with σ and μ which are respectively the effective stresses to which the rocky block is subjected and is the constant coefficient of friction. Numerous works such as those of [1] [46] [47] [48] [49] have shown that the system is highly sensitive to: the variation in the speed of the tectonic plate [50], the variation in the effective stress and the coefficient of static friction. We will therefore focus on these parameters during our numerical simulations.

We varied the static friction force F_0 in order to take into account the effect of the pressure of the medium on the evolution of the temperature. Indeed, knowing that $F_0 = SP_0$, where P_0 and *S* are respectively the pressure exerted by the block of Mass M on the fault plane and the surface on which M is placed and if we admit after dimensioning that our block is of unit section, then we will have $F_0 = P_0$. In doing so, any variation in the force will induce a variation in the pressure of the solution. When simulating temperature as a function of time and displacement, we observed that the temperature increases with the evolution of the statistical force of friction. It was also observed that the temperature evolved with the increase in the depth of the slip zone.

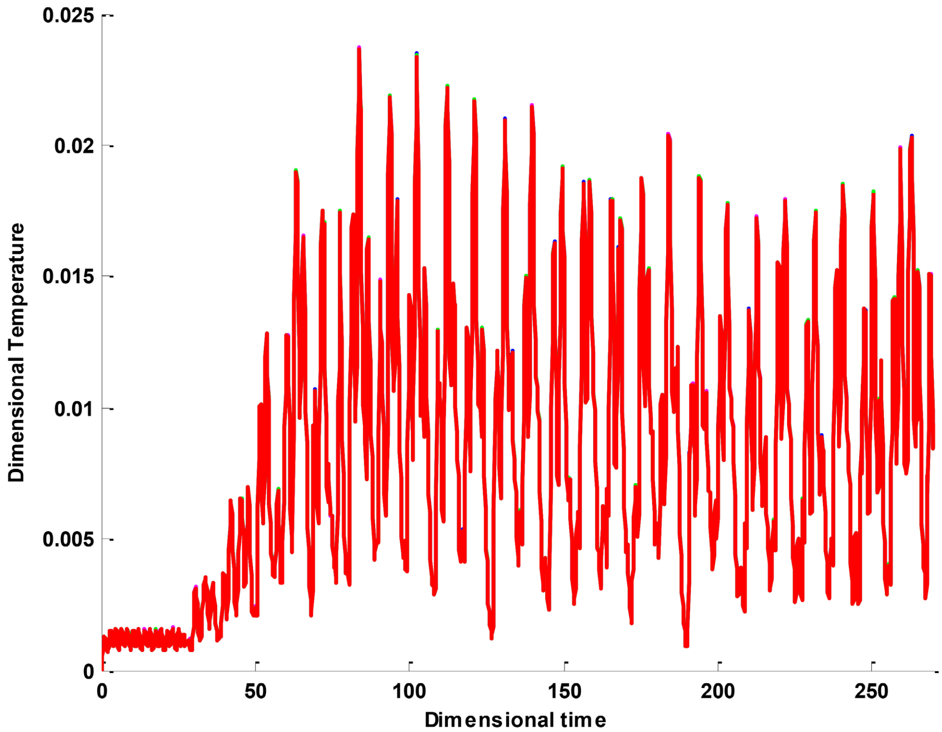
The numerical representations of the solutions of equation Equation (10a) as a function of time and depth are given by the **Figures 2-7**.

The temporal evolution of the temperature shows us that in general when we take into account the fact that the coefficient of friction varies (by varying the pulsation ω), the temperature certainly always increases but no longer in a purely linear way. It presents with smaller intervals, discontinuities in its shape. In addition, it presents in smaller intervals, discontinuities in its form. Moreover, it is noted that for the same values of the control parameters, the values of the curves obtained by taking into account the variation of frictional coefficient are lower than those obtained in the case where this frictional coefficient is considered to be constant.

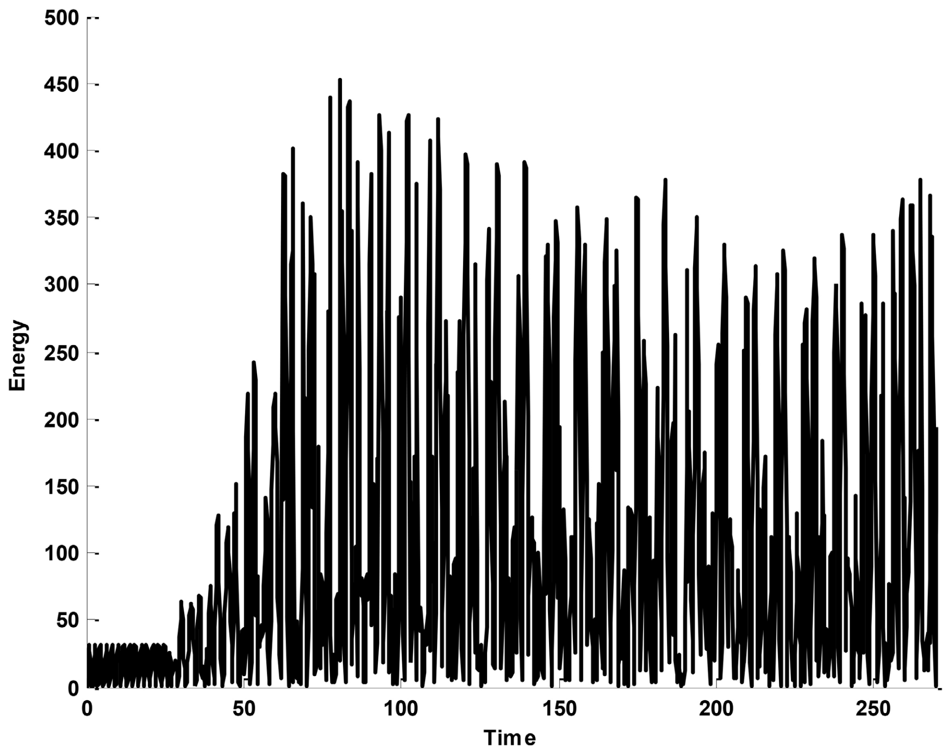
Assuming that frictional coefficient varies sinusoidally with time as the seismic wave propagates underground, we therefore place ourselves at the top of the list in this hypothesis. Thus, it appears from our numerical simulations that the propagation of the seismic signal causes the variation of the temperature of the medium with a sudden increase in the temperature profile as shown in our figures. Assuming that the contact area between two blocks is large, a large part of the energy produced by friction is dissipated in heat causing a local increase in



(a)

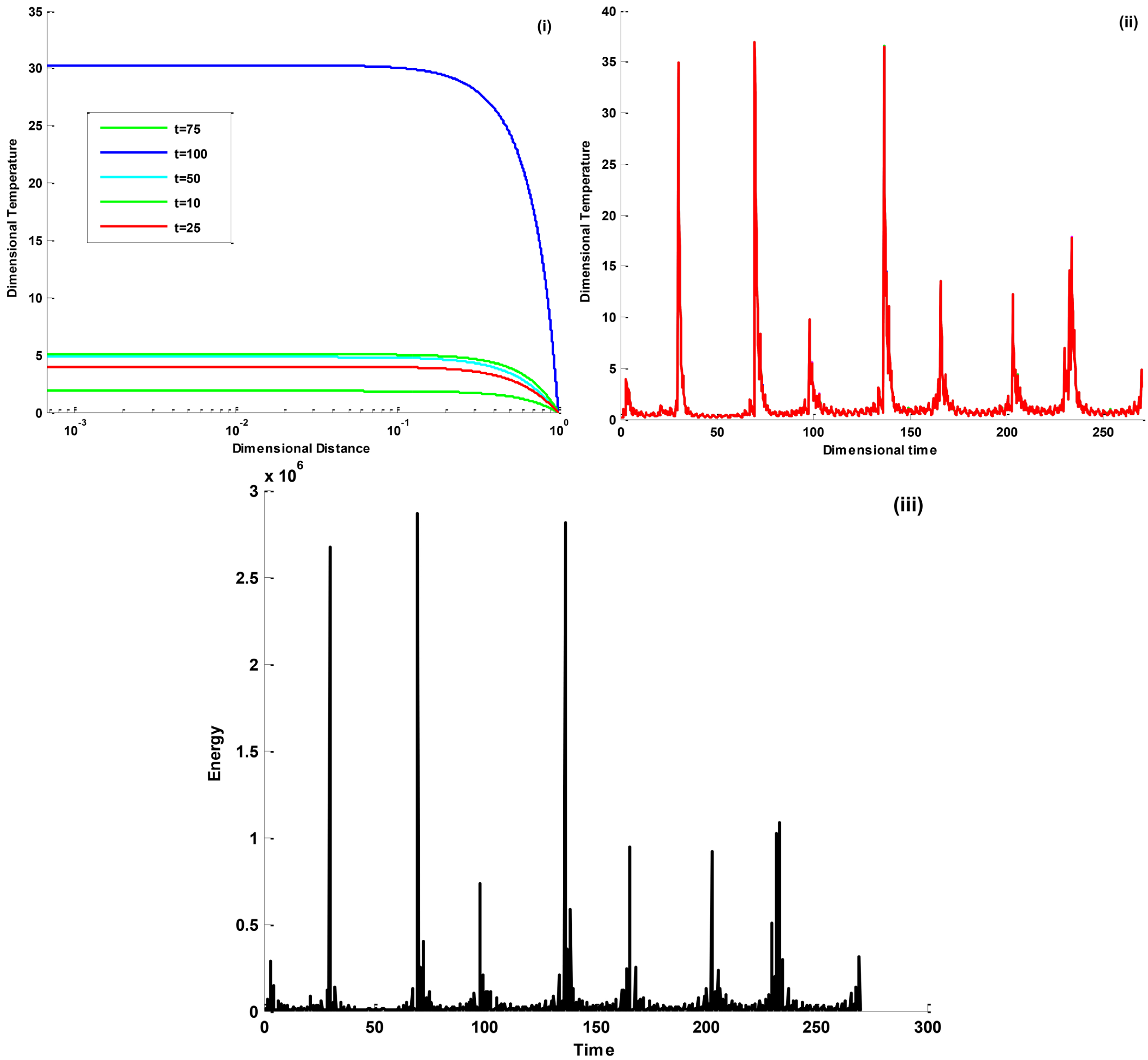


(b)

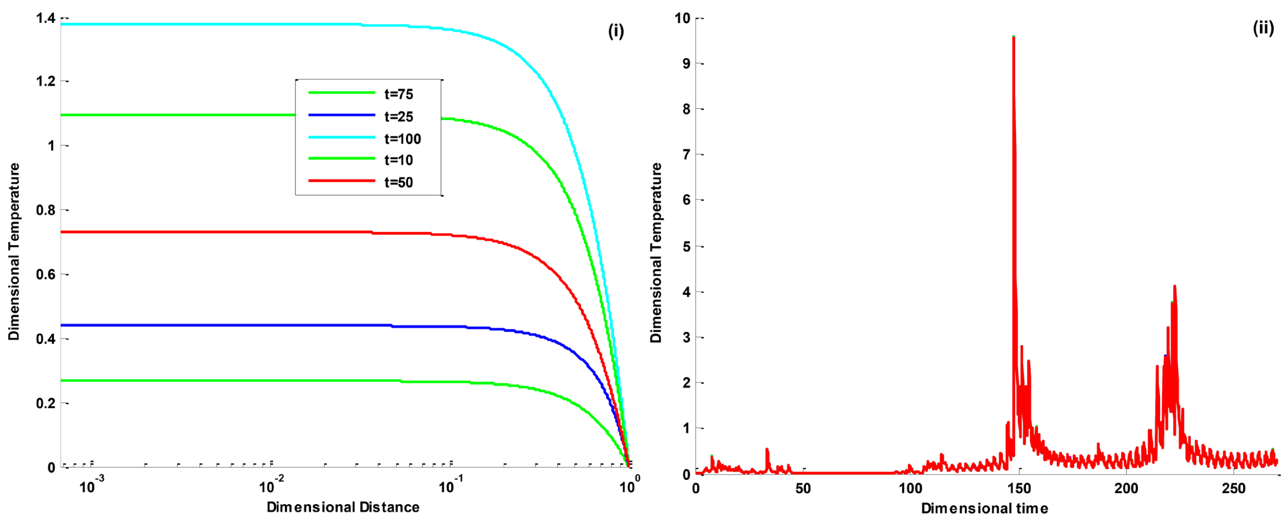


(c)

Figure 2. (a) Temperature change as function of dimensional distance for different value of time; (b) Temperature evolution as function dimensional time; (c) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^{-3}$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 3$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0$, $h = 10^{-3}\ \text{m}$.


(i)
Dimensional Temperature
Dimensional Distance
t=75
t=100
t=50
t=10
t=25
(ii)
Dimensional Temperature
Dimensional time
(iii)
x 10^6
Energy
Time

(a)


(i)
Dimensional Temperature
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t=75
t=25
t=100
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(ii)
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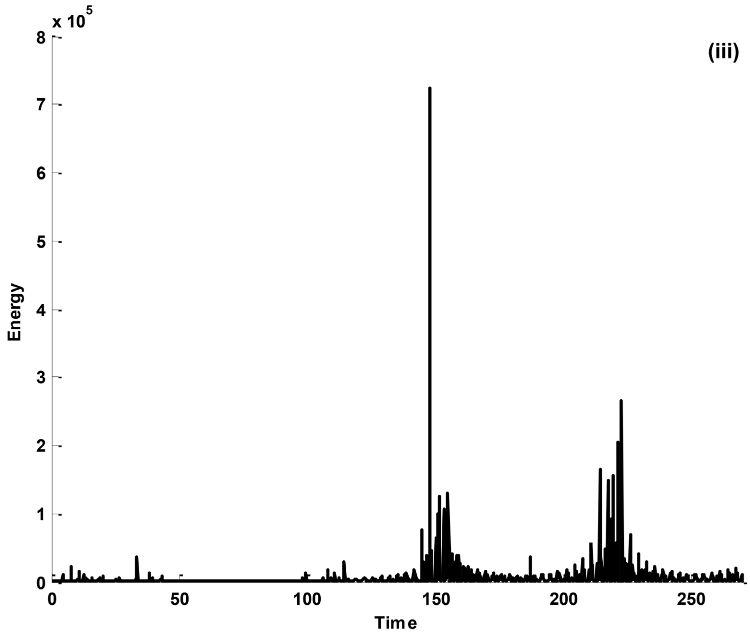

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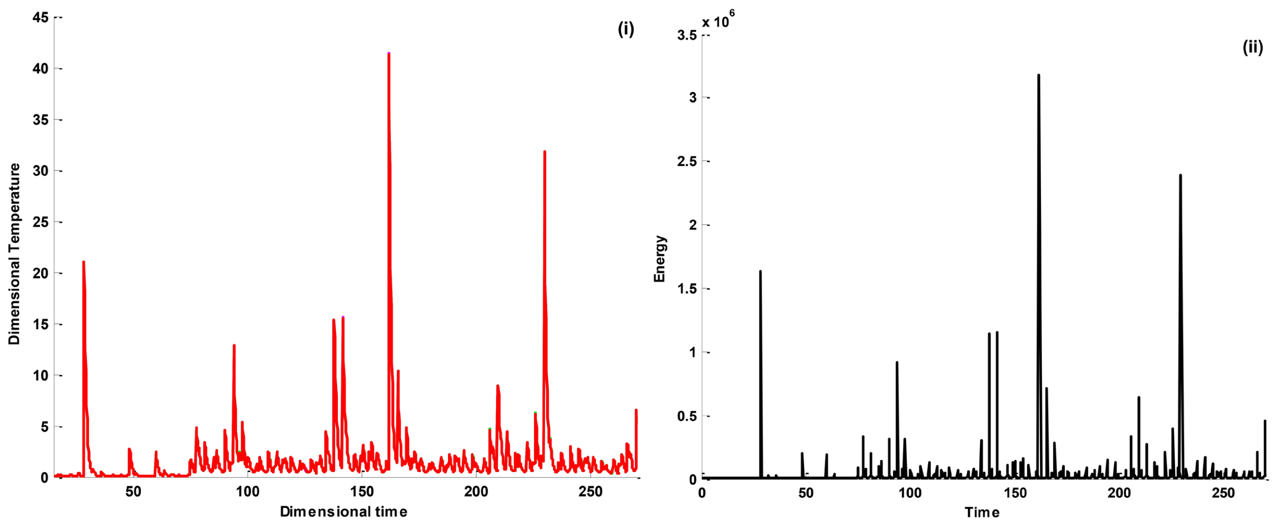
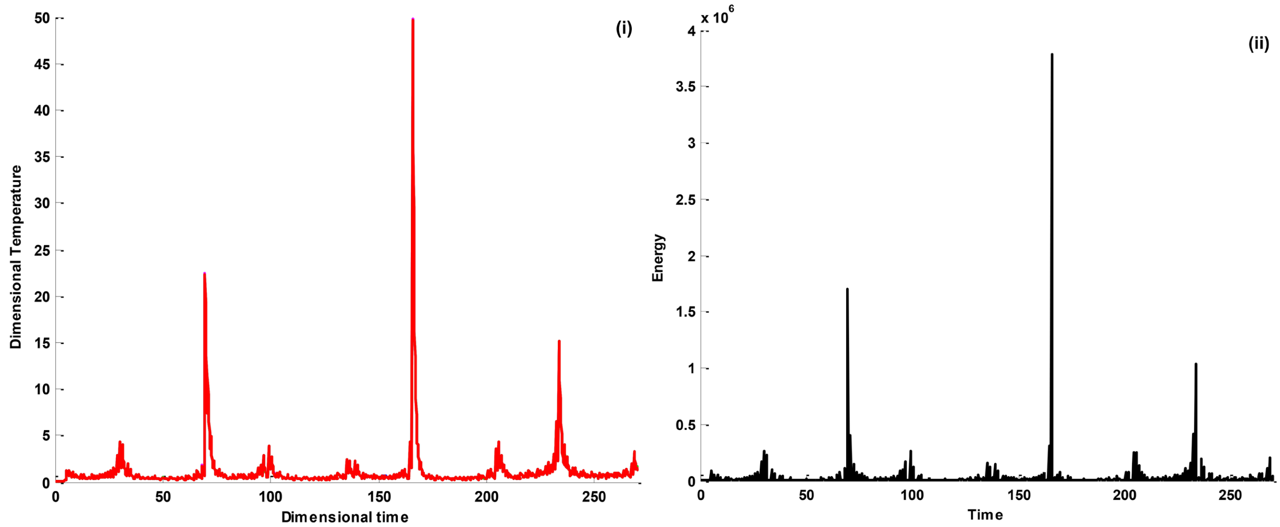


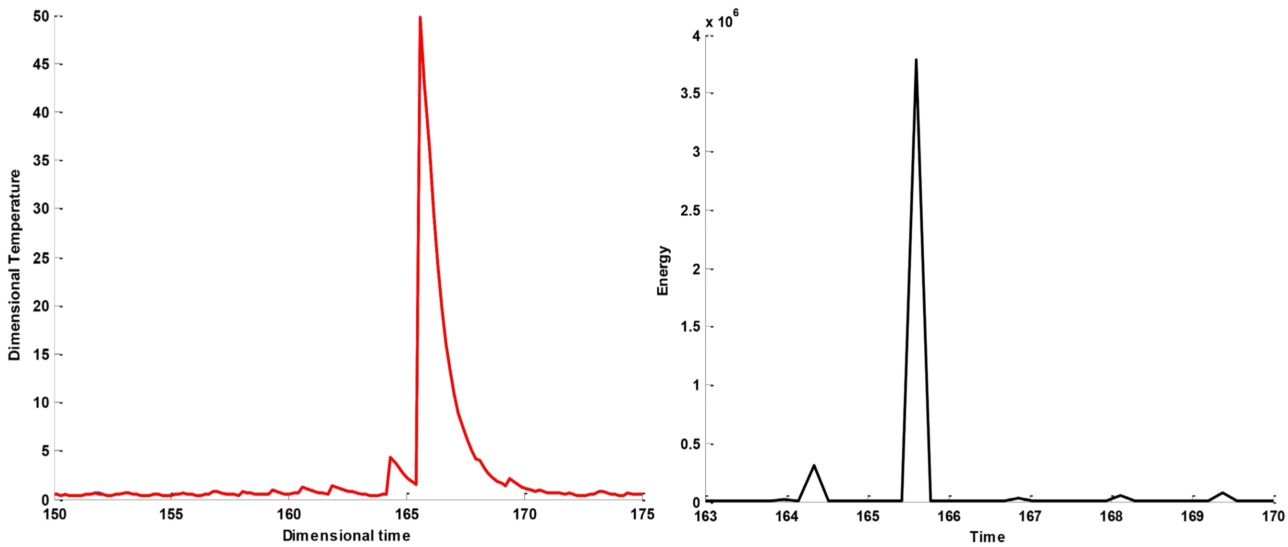
(c)

Figure 3. (a) (i) Temperature change as function of dimensional distance for different value of time; (ii) Temperature evolution as function dimensional time; (iii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 1$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.7$, $h = 10^{-3}\ \text{m}$; (b) (i) Temperature change as function of dimensional distance for different value of time; (ii) Temperature evolution as function dimensional time; (iii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 1$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.6$, $h = 10^{-3}\ \text{m}$; (c) (i) Temperature evolution as function dimensional time; (ii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 1$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.3$, $h = 10^{-3}\ \text{m}$.

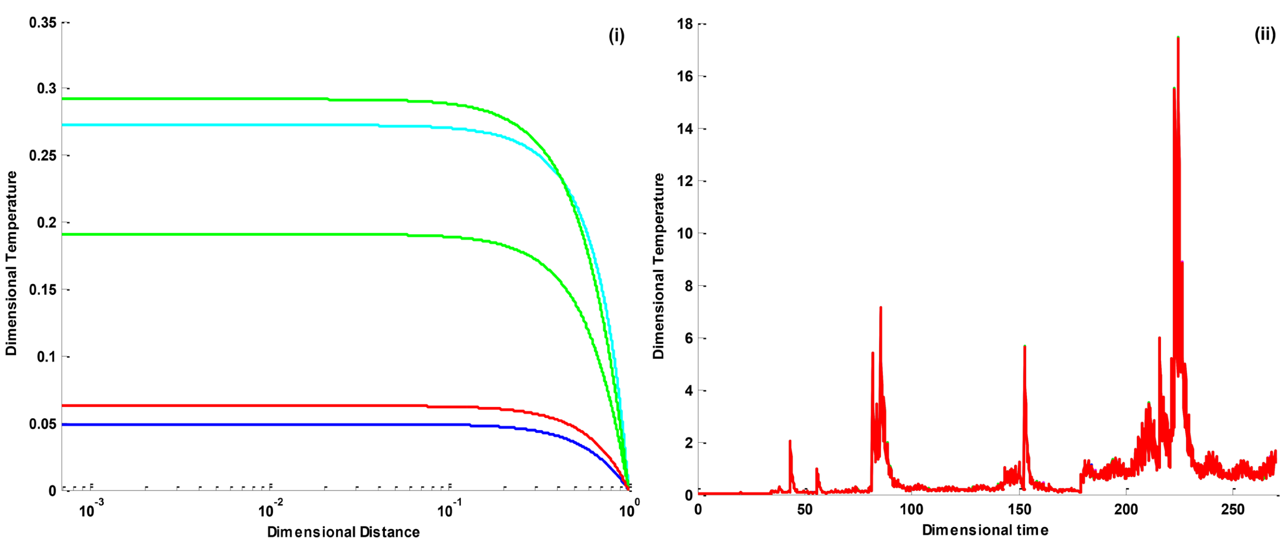
temperature which are generally of very short duration and called flash contact temperature, and this is what justifies the sudden variations with strong spikes in the temperature as observed in our figures in the reduced time intervals, quantity.


(i)
Dimensional Temperature
Dimensional time
(ii)
x 10^6
Energy
Time

(a)


Dimensional Temperature
Dimensional time
x 10^6
Energy
Time

(b)


(i)
Dimensional Temperature
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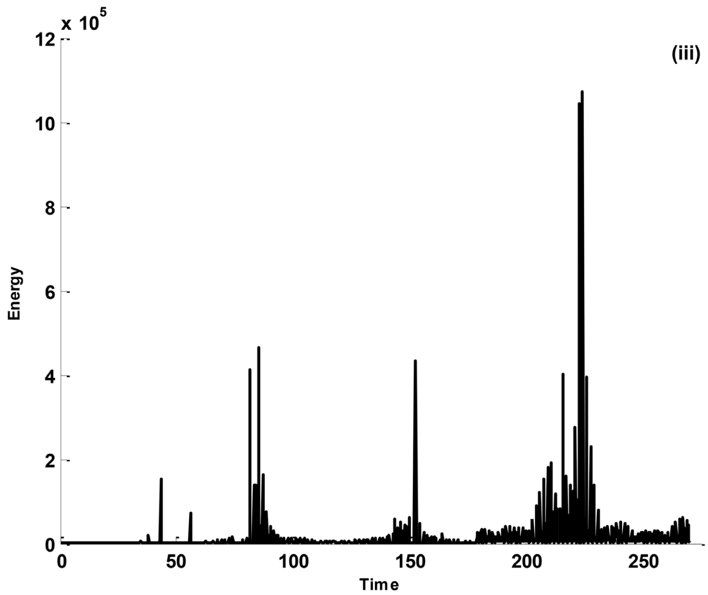
(ii)
Dimensional Temperature
Dimensional time



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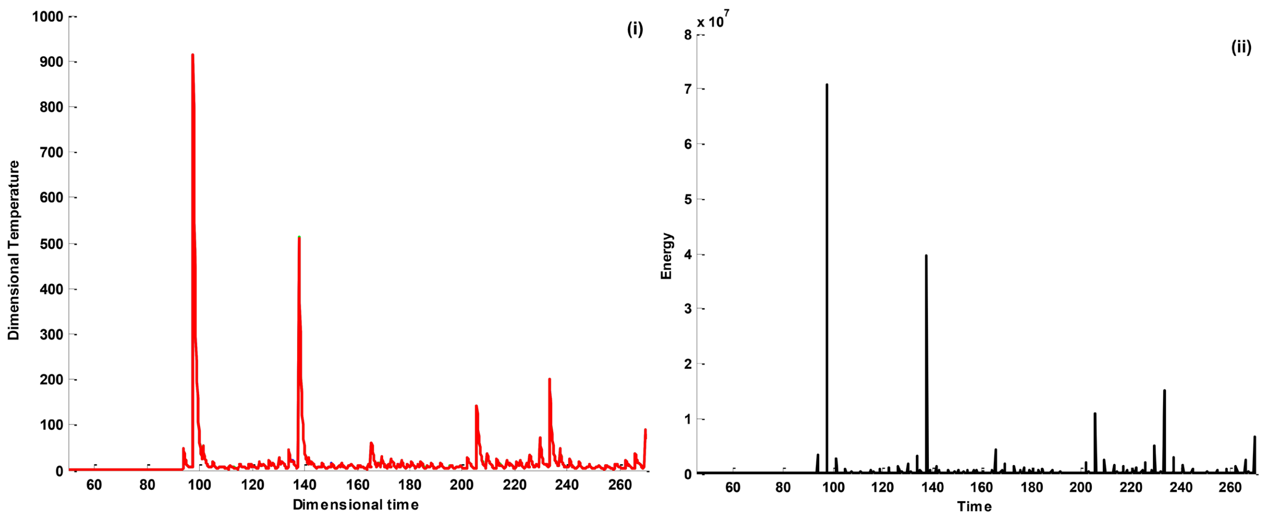
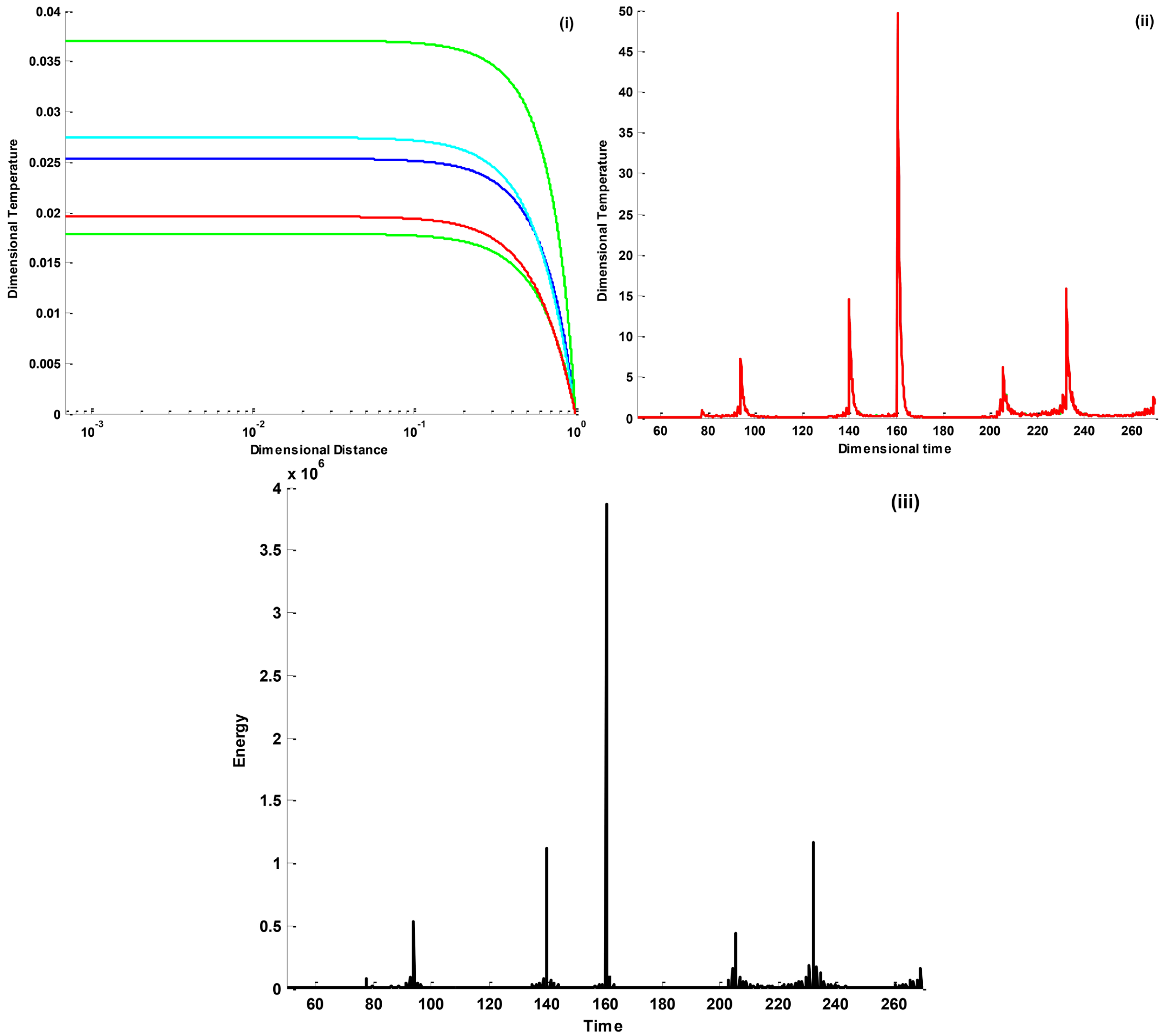


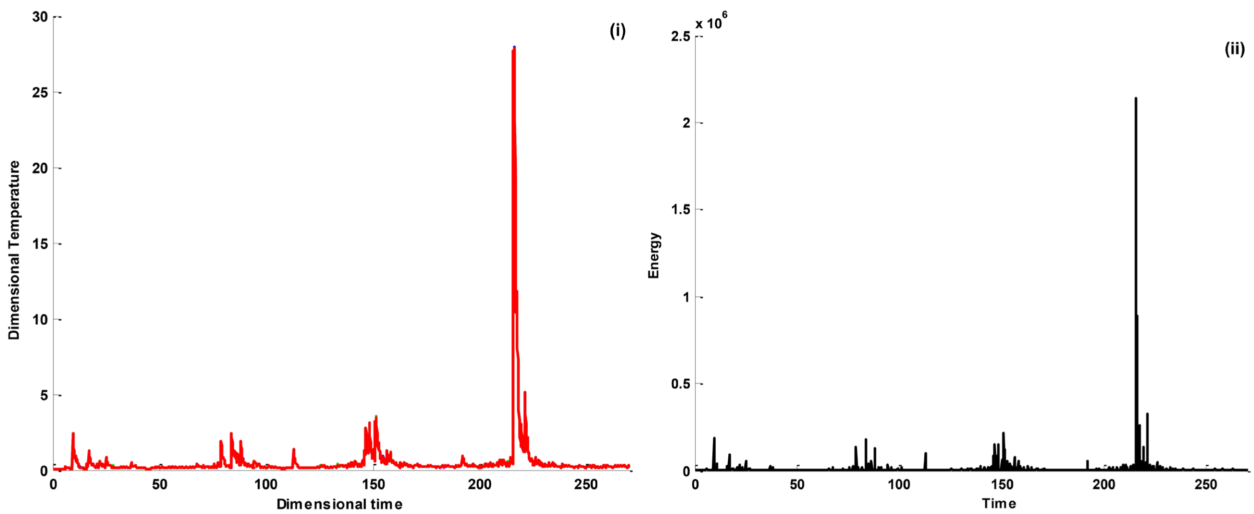
(d)

Figure 4. (a) (i) Temperature evolution as function dimensional time; (ii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 3$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.9$, $h = 10^{-3}\ \text{m}$; (b) $\rho = 2300\ \text{kg/m}^3$, $C_p = 505$, $\lambda = 2.7$, $k = 3$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.9$, $h = 10^{-3}\ \text{m}$; (c) (i) Temperature change as function of dimensional distance for different value of time; (ii) Temperature evolution as function dimensional time; (iii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 3$, $\delta_\gamma = 0.5$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.7$, $h = 10^{-3}\ \text{m}$; (d) (i) Temperature evolution as function dimensional time; (ii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 3$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.3$, $h = 10^{-3}\ \text{m}$.

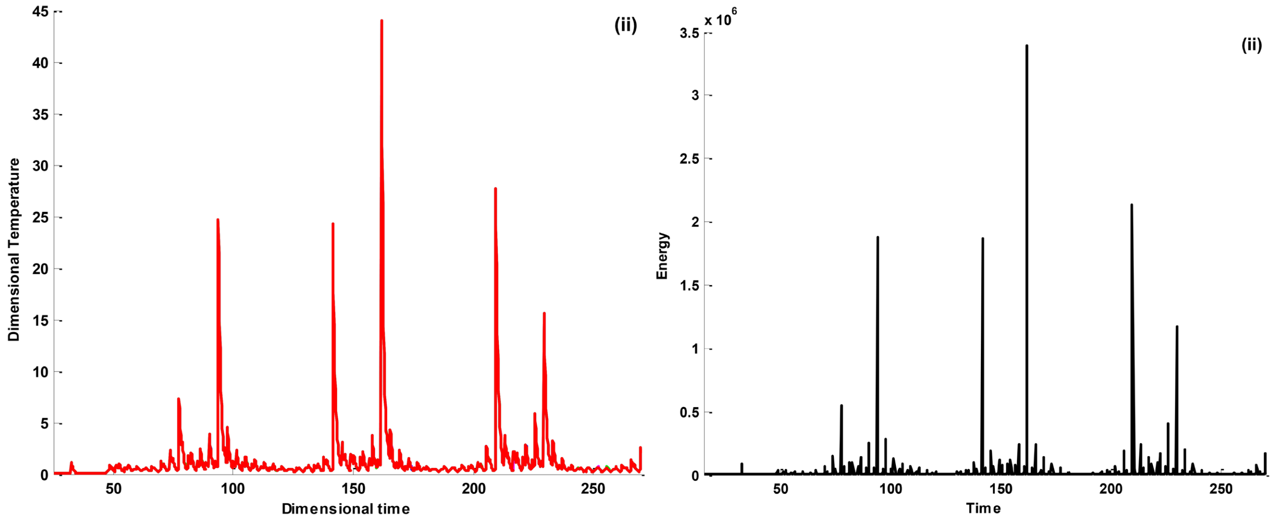
By varying the value of the pulsation ω, one thus varies the coefficient of friction because, the pulsation intervenes there (see Equation (6)). This also affects the temperature as well as the energy produced by friction at the fault lip. So, with the exception made of the case $\omega = 0.3$ (**Figure 4(d)**) and $\omega = 0.7$ (**Figure 6(a)**) for which the variation is not discernible, in general, it emerges


(i)
Dimensional Temperature
Dimensional Distance
(ii)
Dimensional Temperature
Dimensional time
(iii)
x 10^6
Energy
Time

(a)


(i)
Dimensional Temperature
Dimensional time
(ii)
x 10^6
Energy
Time

(b)

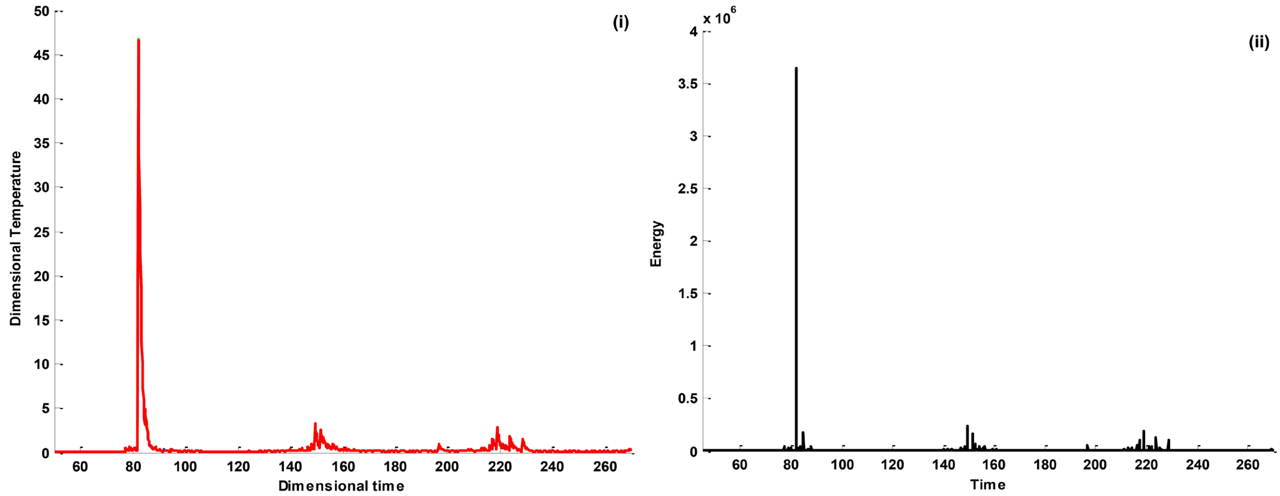


(c)

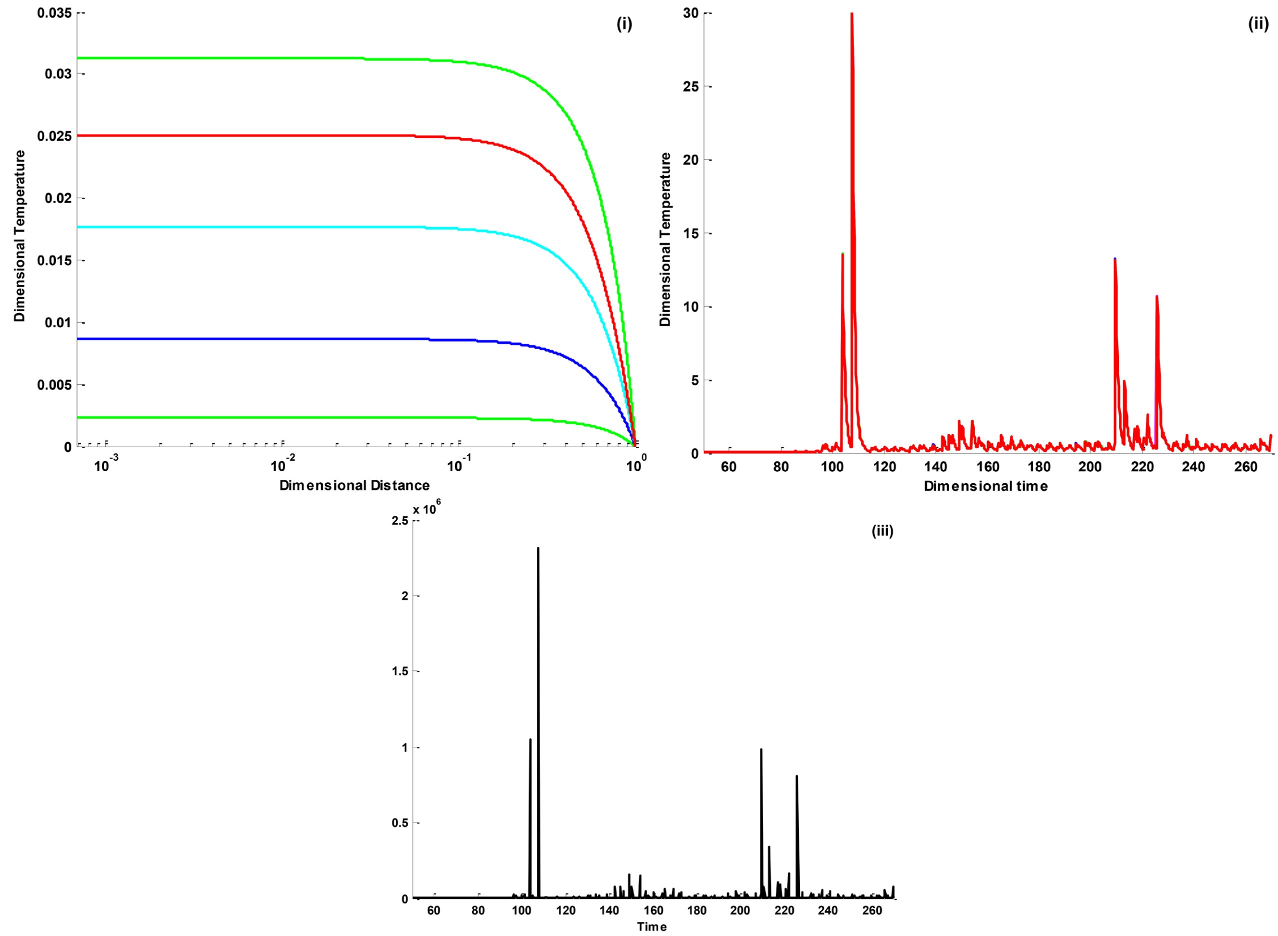
Figure 5. (a) (i) Temperature change as function of dimensional distance for different value of time; (ii) Temperature evolution as function dimensional time; (iii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 6$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.9$, $h = 10^{-3}\ \text{m}$; (b) (i) Temperature evolution as function dimensional time; (ii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 6$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.7$, $h = 10^{-3}\ \text{m}$; (c) (i) Temperature evolution as function dimensional time; (ii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 6$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.3$, $h = 10^{-3}\ \text{m}$.

from our curves that the system is largely sensitive to the variation of ω, moreover we notice the existence of strong variation of temperature and energy before any major seismic event.

By analyzing the figures (**Figures 4-7**) we observe that more we vary the parameter characterizing the frequency ω (therefore the coefficient of friction), the interval between the peaks of the wave also varies. For low values of ω (see **Figure 2**, **Figure 5(c)**, **Figure 6(b)** and **Figure 7(c)**), the maximum value of the temperature change as a function of time is quickly reached and then the temperature decreases exponentially to the imposed initial value. And after a certain time, another cycle begins again but this time with a maximum value of spades lower than the preceding spades. This operation is thus repeated over time at irregular time intervals until the signal is completely canceled. For large values of the parameter ω (**Figure 4(a)**, **Figure 5(a)**, **Figure 5(b)**, **Figure 6(a)**, **Figure 7(a)** and **Figure 7(b)**), a process analogous to the previous case is observed with the difference that, before the maximum peak of temperature, smaller peaks of amplitudes are observed as a function of the variation in the parameter ω, which can be considered as the post-seismic phase (nucleation phase) which is generally observed during the loading phase. And after the largest temperature peak, low amplitude temperature peaks are always observed at irregular time intervals. The irregularity and the non-continuity of the temperature profile can be justified by the fact that during the displacement of the blocks and after the rupture

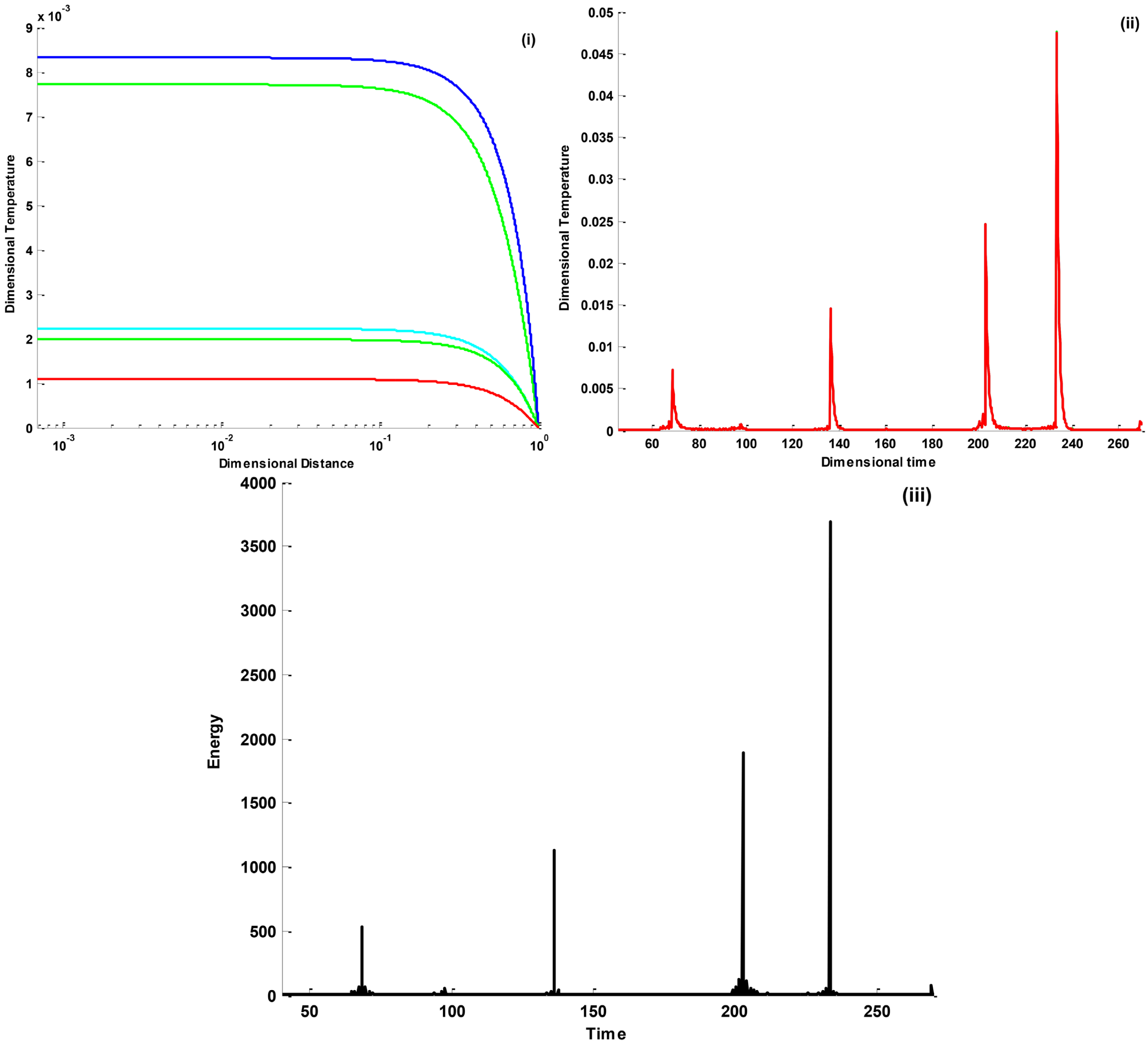


(a)



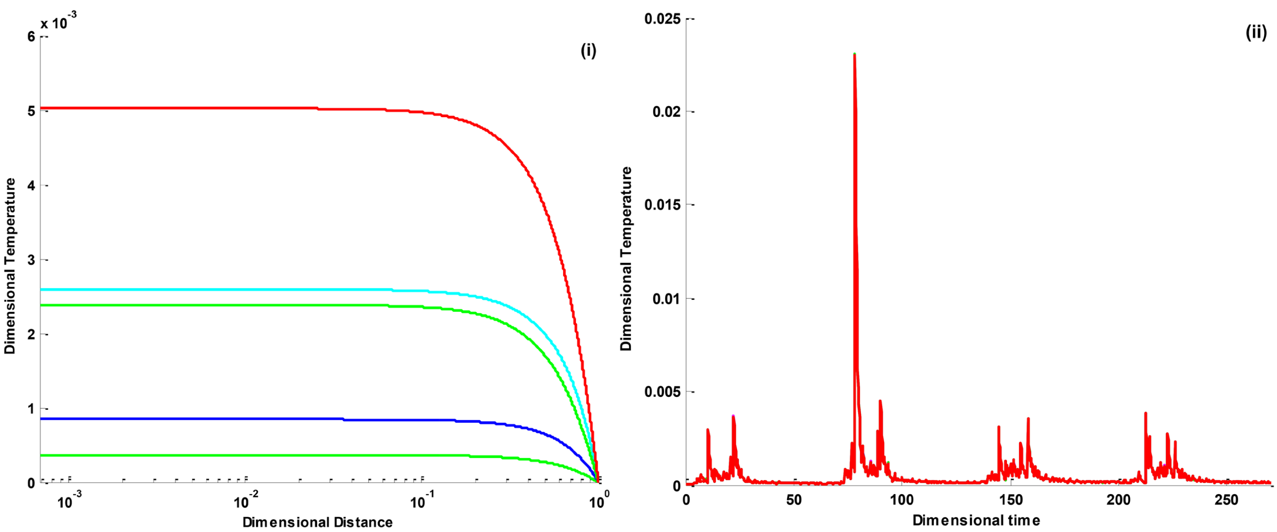
(b)

Figure 6. (a) (i) Temperature evolution as function dimensional time; (ii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2\text{/s}$, $k = 10$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.7$, $h = 10^{-3}\ \text{m}$; (b) (i) Temperature change as function of dimensional distance for different value of time; (ii) Temperature evolution as function dimensional time; (iii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2\text{/s}$, $k = 10$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.3$, $h = 10^{-3}\ \text{m}$.

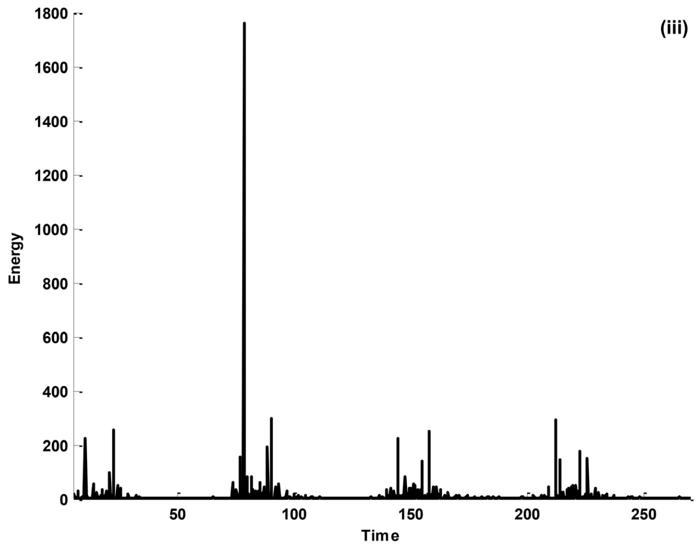


(i)
Dimensional Temperature
x 10^-3
Dimensional Distance
(ii)
Dimensional Temperature
Dimensional time
(iii)
Energy
Time

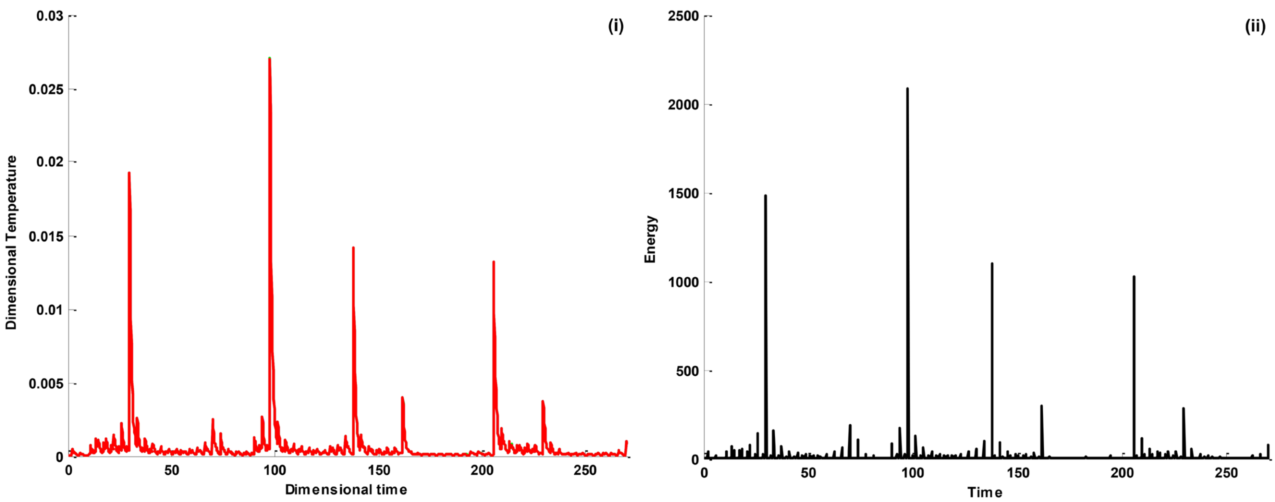
(a)



(i)
Dimensional Temperature
x 10^-3
Dimensional Distance
(ii)
Dimensional Temperature
Dimensional time



(b)



(c)

Figure 7. (a) (i) Temperature change as function of dimensional distance for different value of time; (ii) Temperature evolution as function dimensional time; (iii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 25$, $\delta_\gamma = 90$, $\gamma_c = 40$, $F_0 = 1$, $\alpha = 10^{-9}$, $\omega = 0.9$, $h = 10^{-3}\ \text{m}$; (b) (i) Temperature change as function of dimensional distance for different value of time; (ii) Temperature evolution as function dimensional time; (iii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 25$, $\delta_\gamma = 90$, $\gamma_c = 40$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.7$, $h = 10^{-3}\ \text{m}$; (c) (i) Temperature evolution as function dimensional time; (ii) Evolution of energy as function of for: $\rho = 2300\ \text{kg/m}^3$, $C_p = 505\ \text{J/kg/K}$, $\lambda = 2.7\ \text{m}^2/\text{s}$, $k = 25$, $\delta_\gamma = 90$, $\gamma_c = 40$, $F_0 = 1$, $\alpha = 10^{-9}\ \text{m/s}$, $\omega = 0.3$, $h = 10^{-3}\ \text{m}$.

of the fault, the contact between the two blocks is made only through the micro spikes that the is called roughness on the one hand. Where, on the other hand, it can also be justified by the heterogeneous nature of the earth's crust, hence the fact that it has been accepted that the coefficient of friction follows the shape of the seismic wave. To this end, [30] [31] had apparently obtained curves (**Figure 4(b)**), a figure that we obtained by zooming in on one of our figures.

For values of the coefficient of elasticity between 10 and 20, and as well as for values of thicknesses of the sliding zone greater than 2 mm, the curve representing the change in temperature as a function of time is a straight line and the different curves obtained at different time values are all merged into a single one; As for the representation of the variation of the temperature according to the displacement, it reveals an important evolution of the temperature with more important interval of variation.

For a large value of the coefficient of elasticity, the curves of evolution of the temperature as a function of time and displacement are totally divergent. Indeed, the higher the coefficient of elasticity, the lower the sliding speed of the block (corresponding to the large values of frictional coefficient) and consequently no block movement, and no production of heat by friction. In this practical case, the energy contribution that is recorded in the fault comes only from the thermal radiation of the subterranean heat.

In general, for large values of k and γ ($k \succ 20, \gamma \succ 30$ see **Figure 7**), the temperature as well as the seismic energy produced by friction all grow and admit a threshold value beyond which they decrease towards the value close to the initial value of the system. The system thus disturbed admits relative extremes when the other parameters of the system vary. Moreover, we notice that for the different values of the torque (k, γ), (and for the constant values of the other parameters of the system), the temperature as well as the seismic energy produced friction as a function of time increases with the increase of ω. With $\omega = 2\pi f$ the pulsation and which characterizes the vibratory frequency f of the system.

6. Discussion

In this article, we model the temperature as well as the seismic energy produced by the friction at the level of the fault by considering the variation of frictional coefficient and by admitting the presence of a fluid at constant pressure. For this, we started from 2D Burridge-Knopoff models to generate displacements and velocities. Its displacements and velocities were integrated into the conduction heat transfer equation and the resolution made it to obtain the temperature variation curves as well as the energy produced by friction at the level of the fault for different values of the pulsation ω. To do this, we acted on a characteristic quantity (ω) intervening in the second term of the expression of frictional coefficient, because its variation systematically affects that of frictional coefficient. We focused more on this aspect because many previous works have shown the effect of quantities such as thermal diffusivity and thermal conductivity on the evolution of temperature and the propagation of energy in the Earth's crust. The case where $\gamma = cste$ was not the subject of our analysis, since authors such as [6] [29] and [51] looked into it and showed that the temperature increases with the evolution of frictional coefficient.

The choice of the Burridge-Knopoff model was made because it has the merit of revealing the complex chaotic behavior of an earthquake; and by the law of friction which exists between the blocks and the fixed surface, this model also introduces sources of instability into the system. Moreover, this model is very suitable to study the effect of the variation of the speed (and consequently of frictional coefficient) of sliding on the dynamics of the system. Because, it is proven that the increase in the speed of sliding induces a reduction in the frictional coefficient (and conversely). Authors like [52] showed the importance of small velocity variations on ground shaking simulations. In our case study, this chaotic and unstable behavior of the system was readjusted by admitting that the coefficient of friction was variable. The 2D model that we considered has the merit of integrating through the coefficients of elasticity (taken in each direction of the slip plane) the behavior patterns in compression and in shear of the fault. In order to show the effect of the geometry of the fault on the behavior patterns of the system, we represented for different times, the evolution and the temperature profile during the displacement. It has thus been shown that, the greater the duration of propagation of the wave in the Earth crust, the greater the quantity of heat as well as the temperature released during the propagation of the wave.

The choices of the temporal variation of frictional coefficient were made in order to integrate the geometry of the fault, the properties of the rock, the geology, the friction and the conditions of locking of the fault system such as [33]. Fault geometry plays an important role in earthquake dynamics as shown by [53] and [54]. Indeed, the authors show that, in fault geometry structures in general, link faults play an important role in determining the feasibility of failure propagation through fault crossing. Other justifications for the choice of the variation of frictional coefficient can be found in the work of [55] and [56]. Indeed, the authors show on the basis of a realistic approach [55] that, the variable geometry of the fault includes geologically many small transfers in the fault structure, or an inelastic behavior in the vicinity of the fault junction [56]. By making a temporal variation of frictional coefficient, we also took into consideration the behavior of the creeping parts of the fault (which influences the dynamics of rupture of an earthquake and as well as the place where the earthquakes nucleate), while admitting that they have lost by sliding (during the transient phases that we observe on our curves) part of their deformation energy (for example, [32], [33] [57] [58] [59] [60] [61]).

By considering that the friction coefficient is constant (**Figure 2(a)**), we notice that the inter-seismic period is very low, characteristic of the rock structure. Indeed, by admitting the constant of frictional coefficient, we neglect the effect of the geometry of the fault as well as the effect of the creeping part of the fault which plays an important role during the nucleation phase. Contrary to the case where the frictional coefficient is constant, the temporal variation of frictional coefficient highlights the different transient phases that exist between two consecutive seismic events, while highlighting the inter-seismic period.

Let us recall in practice that for $\omega t = \pi/2$ and $\omega t = \pi$, we have respectively

$\gamma(t)=\gamma_c+\delta_\gamma$ and $\gamma(t)=\gamma_c$ which are all constants. For high values of the induced torque (γ,k), the system is stable and the low values of torque induce a strong instability in the system. Such a conclusion had already been obtained by certain authors such as [38]. The instability due to the low values of the torque (γ,k) (in particular *k*) implies that any disturbance of the system causes strong variations in temperature and therefore in the dynamics of the earthquake. Regarding the sensitivity of the system to the coefficient of elasticity, some authors about [62] and [63] and many others had already underlined the importance of the coefficient of elasticity in the dynamics of rupture of an earthquake fault.

In general, it emerges from the temperature evolution curves as a function of the displacement that it converges towards the same value and all admit a limit value. These curves all have the same concavity and all admit a point of the system beyond which the temperature no longer increases. The temperature profile thus admits a parabolic branch in the plane. Indeed, by observing the curves of the evolution of the temperature as a function of the displacement, we notice that there is a point for which $\lim_{D\to\infty}\left[T(x,y,z,t)-T_{const}\right]=0$, with T_{const} which is the fixed value. This assumes that there is a couple beyond which the temperature evolution curve as a function of the displacement admits a horizontal asymptote of axis the plane (x,y). This asymptote reveals to us that the evolution of the temperature as a function of the lengthening of the seismic fault for different value of time admits a threshold value beyond which the temperature remains constant with the displacement as seen in the figures thus tending towards a stable behavior so we can predict. Which is close to what we find in reality. Indeed, the earthquake being defined as the release of the energy accumulated by friction at the level of the fault lips, this energy cannot be constantly increasing, which implies that there would be a maximum value which, once reached, the temperature remains so until the borderline disturbance that will cause its release.

The variation of frictional coefficient reveals in the profile of evolution of the temperature as a function of time as well as in the profile of evolution of the seismic energy as a function of time a stick-slip motion, which is not the case when the frictional coefficient is constant. Indeed, we observe a strong increase in the temperature as well as in the seismic energy in a very short time interval corresponding to the stick, and which decreases while tending towards a value close to the initial value imposed. Then, after a certain time (slip) corresponding to the (evaluable) nucleation time, the phenomenon repeats itself and so on until the signal is cancelled. This behavior of the system for different values of the control parameters highlights in addition to the stick-slip, the convergence of the system towards a certain a priori stable state when the frictional coefficient varies with time.

The curve of evolution of the temperature shows that it decreases with the reduction of the coefficient of friction and the coefficient of elasticity. Indeed, it is observed during the numerical simulation that, the smaller the coefficient of friction and elasticity, the more the evolution of the temperature as a function of the displacement is a convergent and decreasing curve, tending towards a minimum value located around zero. The evolution of the temperature as a function of time shows us that for certain values of the regulation parameters, the temperature profile is non-linear (see **Figure 4(a-ii)**, **Figure 4(c-ii)**, **Figure 4(d-i)**, **Figure 5(b-i)**, **Figure 5(c-ii)**) contrary to what some authors like [1] [6] and [7] and others had found; this can be justified on the one hand by the fact that the earth is neither linear nor homogeneous, hence the existence of numerous discontinuous zones, or also by the choice of the model (2D) as well as the fact that the coefficient of friction is variable. Indeed, knowing that the earth's crust is an inhomogeneous medium and, knowing that as such, the seismic wave also undergoes modifications and disturbances when crossing a medium of different density. The evolution of the temperature as a function of time must not be a purely increasing curve, it must present variations corresponding each to the different zones of discontinuities crossed by the seismic wave during its propagation as well as to the geometry of the fault. Ambraseys [64] had already predicted this by noting that apart from a sliding movement of the tectonic plates, the plates do not always remain in contact (tight contact) with each other, but only at certain particular points called asperities that ensure permanent contact between the blocks.

Allowing for the varying coefficient of friction (by varying the pulsation), it is clear that the temperature rises sharply with time. Moreover, it is noted that at any significant seismic activity corresponding to the maximum value of the temperatures. Numerous works have made it possible to highlight the temperature variation before any major earthquake without modeling it. The manifestation of this variation is due to the fact that we have admitted the variable coefficient of friction. We also note that the energy produced by friction at the level of the fault undergoes many highly identifiable variations before the great variation of this one. The study of the seismicity of certain regions has made it possible to detect these various temperature anomalies before any earthquake.

With the exception of the figures (cf. **Figure 4(d)** and **Figure 6(a)**), the evolution of the temperature as well as of the energy as a function of time shows the existence of several micro variations (which can be considered as a precursor sign during the nucleation phase) before the occurrence of the large earthquake corresponding according to our model to the maximum values (highest amplitude peak) of the energy as well as the temperature. Then a phase of appeasement in which the energy and the temperature gradually decrease until they cancel each other out. By isolating one of the ridges on one of our figures, we obtain the figure (**Figure 4(b)**) obtained by certain authors such as Fialko, Bizzarri. However, there is a difference between our work and theirs. This difference may be due to the fact that in our resolutions we assumed that the initial values of energy and temperature were zero.

The temperature evolution curves as a function of displacement and time are quite close to that obtained by [30] [31] when he studied the propagation of seismic waves in a heterogeneous medium. Study in which the author modeled the temperature using the Monte Carlos simulation method, with the only difference that our curves show an oscillatory aspect on the evolution of temperature as a function of time. This can be explained by the variable aspect of our coefficient of friction. In this study by Sato, we see that the temperature increases strongly with time in a first phase before this stabilized and converged towards a fixed point for certain values of the parameters of the system, and different from zero for other values of the parameters.

By observing the curves of changes in temperature as a function of time, we see that the temperature increases up to its extreme point, beyond which it begins to decrease to another fixed value different from the initial value. This temperature behavior is quite close to what we encounter in reality. Indeed, the earthquake being a release of energy, before said release there is an accumulation phase in which the system passes from one state to another, and therefore after the release, the system returns to a state equilibrium which can in no way be the initial state of equilibrium of the system before its disturbance. This is also known in the literature as the memory effect of the earthquake [38] [39] and [65].

7. Conclusion

Our study focused on the study of the effect of the temporal variation of the coefficient of friction (by varying the value of the pulsation ω) on the evolution of the temperature as well as the seismic energy produced at the level of the lip of fault. Our study reveals the existence of an inter-seismic phase (transient phase) between two consecutive seismic activities. The introduction of the variation of the coefficient of coefficient induced a stability and a convergence in our system. Taking the variable coefficient of friction, we took into account the geometry (asperity) of the fault as well as the physicochemical properties of the Earth's crust, which allowed us to highlight through our numerical simulations the inhomogeneous nature of the Earth's crust. We have also shown based on this approach that the evolution of temperature as a function of time as well as a function of distance converges. This allowed us to conclude in agreement with the literature that there is a fixed point beyond which the temperature could not increase. Our results also allowed us to highlight the fact that the system subjected to a disturbance cannot return to its initial state once the disturbance is over, it joins another steady state which will be a function of both the constraint and the environment in which the solicitation took place. All these results, if mentioned, allow us to conclude that in addition to taking into account the chemical, geophysical and mechanical characteristics of the subsoil in seismic prevention, it is now also necessary to take into account the variation of the coefficient of friction.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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