Title "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.

Keys words: Earthquakes; coefficient of friction; fault lip; temperature variation; energy variation; asperity point.

Plain Language Summary

In this draft article, we model by mains of mathematical expressions, the thermal energy produced by friction at the level of the lip of fault as well as the variation of the temperature occurs by friction at the level of the lip of fault by admitting the variation of coefficient of friction. The results which we obtained are interesting and especially carrying the object of a publication. We showed in this work that :

Slip generated at the level of fault occur a variation of temperature on specific points called asperity.

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 crust's.

1- 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 (Fialko, 2004), but some indirect estimates suggest that frictional losses may constitute a significant part of the earthquake's energy budget (Kanamori and Anderson, 1975; McGarr, 1980; Scholz, 1990; Fialko, 2004). Thermal perturbations associated with seismic slip-on faults may significantly affect the dynamic of friction and the mechanical energy release during earthquakes (Fialko, 2004). Before earthquakes, we observe more anomaly in area of earth like a deformation of rocks allows accumulation of stress energy (Gao and Crampin, 2004; Konga et al., 2017, 2019). According to numerous studies (Bizzarri, 2009a, 2009b, 2010; Noda et al., 2009), the temperature felt generated on the fault surface is responsible to a large number of physical (Andrews, 2002; Sibson, 2003; Rice, 2006) and chemical dissipation process (Hebert et al., 2009; Kuge et al., 2010; Van Keken et al., 2003, 2011) and by consequence frictional heat on a sliding interface. Mair and Marone (2000) observe a dramatic weakening effect or reduced of heat production occur during dynamic slip. With the same idea, Hirono et al., (2006a, 2006b, 2007) reported high magnetic susceptibility and low inorganic carbon content from the fault gouge of the Taiwan Chelungpu fault, that might have resulted from the formation of magnetic minerals from paramagnetic minerals (Mishima et al., 2006), and thermal decomposition of carbonate minerals respectively (Hirono et al., 2008) before earthquakes**.** Few years ago, Kuo et al., (2005) reported relatively low contents of clay minerals within the Chelungpu fault, and suggested that frictional heating during an earthquake had induced dewatering of clay mineral. According for a last earthquake, more studies and more authors prove that we observe variation of temperature before earthquakes. Sibson (1977) and Lachenbruch (1980) admit that the coseismic increases of temperature may affect the frictional properties of rocks in the fault zone, and the dynamic stress drop during earthquakes. Li et al., (1998) shows that, before earthquakes, we are also observed anomaly of temperature. Most studies of stick-slip friction focus on the dynamic motion during slip because of its importance in generating vibrations, heat, wear, and some cases, seismic radiation (Marone and Saffer, 2015). During the pre-existing phase of seismic, the temperature increases with displacement at the level of fault lip. More studies permit to model this temperature. Schotz (1990) is one of first who showed the energy balance for faulting (Di Torro et al., 2005), she admits that, this energy is equal to some of heat, energy released as seismic waves, work for fault surface refinements and gouge format and the work against gravity (Di Torro et al., 2005; Scholz, 1990). Mair and Marone (2000) show during their studies on one-dimensional heat-flow solution for frictional heating in a finite width layer that, the measure of temperature as level of fault increases systematically with friction shear and velocity. Konga et al., (2017) modelled this energy using the first principle of thermodynamic; Konga et al. (2019) models the seismic energy produced at the fault lips for different law of friction, taking into account the influence of the viscosity. Their studies permit to obtain that, the temperature distribution decrease when going far from the slip zone. Angisboust et al. (2012) studies the importance of fluid circulation on tectonic subduction interface processes taking into account thermo-mechanical processes. During his studies, the authors prouve that the circulation of fluid along the subduction interface is strongly at originally of the discontinuous mafic crust. Nielsen et al. (2008) studie the effer of frictional melting on the processes of seismic slip. Noda et al. (2009) studie the rupture of earthquakes taking into account of the thermal weakening opered into a fault. Their autor's proove that efficiency of thermal pressurization is important to determined the average stress doing work within ruptures at larger amounts of slip than those we have been able to model in this work. Hu and Sun (2019) study the effet of high temperature and pressure on rock friction coefficient. he proove in general that, the value of coefficient of friction increase when the value of temperature increase.

All of its authors modeled the thermal energy and the temperature generated by friction at the fault lip without assuming that the coefficient of friction was constant. However, due to its internal structure and the divergence of its composition, several authors (Sato and Fehler, 2009; Sato et al., 2012) have shown that the earth's crust is a heterogeneous environment. Thus, we will not be able to admit that the coefficient of friction is constant. In this work, we propose to model the temperature produced by friction at the level of the fault lip by taking into account the variation of the friction coefficient. Then we will identify the effect of the variation of the coefficient of friction on the temperature as well as on the energy produced by friction at the level of the fault lip. We will also consider that the seismic energy product by friction at level of fault is equal to work done of friction force during the same movement.

2- Description

Earthquakes are created when the energy accumulated by friction at the fault lips is suddenly released. The magnitude and magnitude of said earthquakes are strongly related to this energy produced. A large number of works (Scholz, 1990; Bizzari, 2004; Di Torro, 2004) have shown the existence of several forms of energy at the level of the fault lips and therefore the most important was the energy accumulated by friction at the level of the lip's faults. For this purpose, Scholz (1990) and Fialko (2004), propose that the energy balance for faulting is giving by the relation:

$$W_f = Q + E_s + U_s + W_g \quad (1)$$

According to the author and literature, Q is the heat, E_s is the energy reloaded as seismic waves, U_s is the work for fault surface, W_g is the work against gravity and W_f is the work done in faulting including friction and ductile deformation. According to its study Di Torro (2005), Lockner and Okubo (1983), MrGarr (1999) shows that E_s are neglected in front of total energy related by an earthquake; U_s are also neglected according to Scholz (1990) and $W_g \approx 0$. Taking all this approximation, Eqs. (1) become:

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

This relation Eqs. (2) proved that most of energy dissipated on a fault is ultimately converted into heat (Fialko, 2004). The work done generated by friction as mathematically define by relation below:

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

In this relation, $\vec{F}$ is a frictional force as level of fault slip, $\vec{v}$ is vector velocity of spring block define by relation Eqs. (4b), h and θ is a volume of spring block. We note that the work done generated by friction $Q(x,y,z,t)$ in reality equal to the work of force necessary to bring up the spring block on (x,y) plane. 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 Montagne and Vasconcelos (2004) in 2D taking into account the friction function Eqs. (4a).

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

$$v = \sqrt{\dot{x}^2 + \dot{y}^2} \tag{4b}$$

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

Where F_0 represented the statistical friction force, γ_c is the coefficient of friction, and ϕ is the function of friction define by Eqs. (4c). The speed defined in Eqs. (4b) are the solutions of the differential equation introduced and defined by Ito et al., (2001) translating the 2D dynamics of an earthquake and defined by:

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

Where $\varphi_{fr} = \pi + \varphi_{el} - (\varphi_{el} - \varphi_{vr})\left[1 - \exp(-\Omega v_r)\right]$, is the angle who giving the direction of friction force with tectonic plaque; k anisotropy parameter; γ_c is the friction 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 (Montagne and Vasconcelos, 2004) (see Fig. 1).

3- Influence of coefficient of friction

By definition, the coefficient of friction is the response of a pair of material to an external stress in a given environment. It is generally due to adhesive forces located at the points of true contact (Rabinowicz, 1965). Several factors can influence the coefficient of friction, namely the mechanical properties of materials, surface parameters or even environmental parameters, roughness, sliding speed or temperature (Rabinowicz, 1965; Briscoe and Tabor, 1975) on the one hand and the other is independent of the macroscopic contact area but proportional to the real contact area (Bowden and Tabor, 1950, 1954). In their work, the authors report that the real surface involved outside the friction presents a microscopic roughness and it is the sum of the microscopic contacts that makes the real contact. However, in addition to the work of (Bowden and Tabor, 1950, 1954), other work in the literature has also shown that the coefficient of friction at the macroscopic scale integrates the distribution of heights, the geometry of the 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 taking into account the elementary contribution of each contact between antagonistic roughness (Rabinowicz, 1965; Briscoe and Tabor, 1975). The seismic wave does not propagate uniformly over time, and numerous related works in the literature prove this. Moreover, knowing the propagation of the seismic wave induces disturbances of the temperature of the incident medium and that the coefficient of friction is sensitive to the variation of the temperature, we will admit the latter takes place at the frequency of vibration of the wave. seismic and time by the relation Eqs. (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 create a temporal variation of the coefficient of friction by analogy to the work of Kostic et al., (2014). 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 Eqs. (6), γ_c is the constant of friction, δ_γ is a characteristic parameter of the medium and $\omega = 2\pi f$ which is the pulsation and is characteristic of the f vibrational frequency of the system. γ_c and δ_γ, being constants characteristic of the system, in order to have the effect of the 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 (Fialko, 2004) and define by relation Eqs. (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.

In the rest of our work, we will dimension the equation Eqs. (7). For that, we're consider the new dimensioned variable z^* and t^* define by: $t^* = \frac{\alpha t}{H^2}$ (who corresponding to $\Delta t^* = \frac{\alpha . \Delta t}{H^2}$, this was the increase temperature due to fault slip in the plane (x, y)) and $z^* = \frac{z}{H}$,in which H is the depth of fault and, $\alpha = \frac{\lambda}{\rho C_p}$ is the heat diffusivity of medium. Taking this news dimensional value z^* and t^* in equation (7), we obtain the equation with dimensional value; and after that, if we return to original variable z and t, equation Eqs. (7) become:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} + \frac{Q.H^2}{\lambda} \tag{8}$$

To solve the equation Eqs. (8), we discretize it and obtain the equation:

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

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 Eqs. (9) is given by conjecture by the relation:

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

With conditions :

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

4- Numerical simulation

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 would come back to the case $\gamma = cnste$ 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 $\omega = 0$ (Fig. 2) to that obtained by Bazzarri (2011), 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. 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 the coefficient of friction 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 the coefficient of static friction, numerous works with regard to Fialko, 2005; Bizzari and Cocco, 2006a, 2006b; Bizzarri, 2005, 2009(a, b), 2012, and many others have shown that the system is strongly sensitive to the speed instead of the effective stress and the coefficient of static friction. So, we will focus more on these cases 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 is also observed that the temperature changes with the increase in the height of the sliding zone.

The numerical representations of the solutions of the equation Eq. (10a) as a function of time and depth are given by the Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6 and Fig .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 is noted that for the same values of the control parameters, the values of the curves obtained when taking into account the variation of the coefficient of friction are lower than in the case where this constant coefficient is considered.

Assuming that the coefficient of friction varies sinusoidally with time such that the seismic wave also propagates in time, we thus place at the top of the list in this hypothesis. Thus, it emerges from our numerical simulations that the propagation of the seismic signal which causes the variation of the temperature of the medium causes 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 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. Moreover, according to the work of (Rabinowicz, 1965; Briscoe and Tabor, 1975), it is known that the coefficient of friction is a relatively unstable quantity.

By varying the value of the pulsation ω, one thus varies the coefficient of friction because, the pulsation intervenes there (see Eq.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 $\omega = 0.3$ (Fig. 4d) and $\omega = 0.7$ (Fig. 6a) for which the variation is not discernible, in general, it emerges from our curves that the system is largely sensitive to the variation of ω, moreover we notice the existence of strong variation of the variation of temperature and energy before any major seismic event.

By analyzing the figures (Fig. 4, Fig. 5, Fig. 6 and Fig. 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 Fig. 2, Fig. 5c, Fig. 6b and Fig. 7c), 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 (Fig. 4a, Fig. 5a, Fig. 5b, Fig. 6a, Fig. 7a and Fig. 7b), a process analogous to the previous case is observed with the difference that, before the maximum temperature peak, peaks of smaller amplitudes are observed as a function of the variation in the parameter ω, which can be accepted as the post-seismic phase where loading and, after the greatest peak, temperature peaks are also observed, always at irregular time intervals. The irregularity and non-continuity of the temperature profile can be justified by the fact that during the movement of the blocks and after the rupture of the fault, the contact between the two blocks is only made through the micro points that the one calls roughness on the one hand. On the other hand, it can also be justified by the heterogeneous character of the earth's crust, where the fact that we have accepted that the coefficient of friction follows the shape of the seismic wave. To this end, Sato and Fehler, 2009; Sato et al., 2012 had apparently obtained curves (Fig. 4b) that we obtained by zooming 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 2mm, the curve representing the temperature as a function of time is a straight line and the various curves obtained at different time values are all merged into one; As for the representation of the temperature as a function of the displacement, it reveals a significant evolution of the temperature and a greater interval of variation.

For a large value of the elasticity coefficient, the curves of evolution of temperature as a function of time and of displacement are totally divergent. In fact, the greater the coefficient of elasticity, the more the block is opposed to an external stress, consequently no block movement, no friction, no heat production and no increase in temperature at the level of the future fault zone.

In general, for large values of k and γ $\left(k \succ 20, \gamma \succ 30\right)$ see Fig. 7, the temperature and the seismic energy produced by friction all increase and admit a maximum threshold value beyond which it decreases towards the value close to the initial value of the system. The system thus disturbed admits extremes relating to the variation of the intrinsic parameters of the signal. In addition, we notice for the different values of the torque $\left(k, \gamma\right)$, by keeping the other parameters of the system constant, the evolution of temperature and energy as a function of time increases with the increase of ω. With $\omega = 2\pi f$ which is the pulsation and is characteristic of the f vibrational frequency of the system.

5- Discussion

In this work, it was a question for us to study the effect of the variation of the coefficient of friction on the dynamics of propagation of the earthquake. To do this, we acted on the characteristic quantity ω intervening in the second term of the expression of the coefficient of friction so, the variation systematically affets that of the coefficient of friction. Afterwards, we only retarded on this aspect because many previous works have shown the effect of quantities such as thermal diffusivity and thermal conductivity on the dynamics of temperature and energy propagation many other works have also studied the case where $\gamma = cste$, and we see that the temperature increases with the evolution of the coefficient of friction. Hu and Sun (2019); Konga et al., (2019); Shelton et al., (1981) came to the same conclusion.

The temperature curve shows that it decreases with the decrease in the coefficient of friction and the coefficient of elasticity. Indeed, we observes during the simulation that, more the coefficient of friction and elasticity is small, the evolution of the temperature according to 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 control parameters, the temperature profile is non-linear (see Fig. 4a(b), Fig. 4c(b), Fig. 4d(a), Fig. 5b(a), Fig. 5c(b)) curve contrary to what certain authors such as Fialko (2014), Konga et al. (2017, 2019) and others had found; this can be justified on the one hand by the fact that the earth's is neither linear nor homogeneous, hence the existence of many discontinuous zones, where also the fact that we have accepted that the coefficient of friction is variable.

Indeed, knowing that the earth's crust being non-homogeneous medium and, knowing that as such, the seismic wave also undergoes modifications and disturbances during the crossing of a medium of different density compared to the preceding medium. The evolution of the temperature as a function of time should not be a purely increasing curve, it should present variations each corresponding to the different zones of discontinuities crossed by the seismic wave during its propagation. Ambraseys (1969) had already predicted this by noting that, outside of a sliding movement of tectonic plates, the plates do not always remain in contact (tight contact) with each other, but that certain points exist. called asperities which ensure permanent contact between the blocks.

By admitting the variable coefficient of friction (that to say by varying the pulsation ω), it is clear that the temperature increases strongly with time. In addition, we note that before any large seismic activity corresponding to the maximum value of temperatures, we always observe small fluctuations in the temperature of the medium. A large number of works have made it possible to highlight the variation in temperature before any major earthquake without, however, modeling it. The demonstration of this variation is due to the variation of the coefficient of friction. We also note that the energy produced by friction at the fault lip undergoes many variations in strongly identifiable energy before the large variation in the latter. The study of the seismicity of the region would be well worth detecting these different variations before any earthquake. Understanding this energy analysis would predict earthquakes.

With the exception of figures (see Fig. 4d and Fig. 6a), the evolution of temperature and energy over time shows the existence of several micro variations that we accept as a precursor sign before the advent of the large corresponding earthquake according to the analysis of our figures at the maximum value (peak of greater amplitude) of energy and temperature. Then a calm down phase in which the energy and temperature gradually decrease until they cancel each other out. By isolating one of the pancakes on one of our figures (Fig. 4b) of evolution of energy and temperature as a function of time, we obtain the figure obtained by certain authors with regard to Fialko, Bizzarri obtained similar result in their work. However, a difference is observed in our work relating to the fact that in our resolutions we admitted that the initial values of energy and temperature were zero.

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 temperature evolution curves as a function of displacement and time are quite close to that obtained by Sato and Fehler (2009) and Sato et al., (2012) 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 (Ryabov and Ito, 2001; Montagne and Vasconcelos, 2004; Kostic et al., 2013)

Recall for all practical purposes 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. Large torque values (γ, k) induce system stability and small value of torque (γ, k) induce high system instability. Such a conclusion had already been obtained by certain authors with regard to Montagne and Vasconcelos (2004). Instability due to small values of the torque (γ, k) (particularly k) implies that any disturbance of the system causes large variations in temperature and hence of the dynamics of the earthquake. Relating to the sensitivity of the system with the coefficient of elasticity, certain authors with regard to Simmons and Wang (1971) and Simmons and Nur (1968) and many others had already pointed out the importance of the coefficient of elasticity in the dynamics of failure of a seismic fault.

6- Conclusion

Our study focused on the study of the effect of the variation of the coefficient of friction (by varying the value of pulsation ω) on the temperature produced at the level of the fault lip. Our study reveals that the temperature increases with the increase in the value of the coefficient of friction, both for cases where the coefficient of friction varies with time, and for values where it is constant. In addition, we have shown that when the coefficient of friction varies, the curves giving the evolution of the temperature as a function of time were not fine, they evolve by oscillating following the contact (asperity) between the seismic plates. We have also shown on the basis of this approach that the evolution of temperature converges as a function of time as well as of distance. This allowed us to conclude in agreement with the literature that there is a fixed point beyond which the temperature could not decrease or increase. Our results have also enabled us to highlight the fact that a system subjected to a disturbance cannot return to its initial state once the disturbance is completed, it rejoins another stable state which will be a function of both the stress 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, we must now also take into account the variation in the coefficient of friction.

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Figures captions

Figure 1: 2D model of block M

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: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 3$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0$ $h = 10^{-3}$

Figure 3a : 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 : $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 1$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.7$ $h = 10^{-3}$

Figure 3b : 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: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 1$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.6$ $h = 10^{-3}$

Figure 3c : a) temperature evolution as function dimensional time; b) evolution of energy as function of for: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 1$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.3$ $h = 10^{-3}$

Figure 4a : a) temperature evolution as function dimensional time; b) evolution of energy as function of for: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 3$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.9$ $h = 10^{-3}$

Figure 4b : $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 3$, $\delta_\gamma = 0.4$, $\gamma_c = 0.9$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.9$ $h = 10^{-3}$

Figure 4c : 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: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 3$, $\delta_\gamma = 0.5$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.7$ $h = 10^{-3}$

Figure 4d : a) temperature evolution as function dimensional time; b) evolution of energy as function of for : $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 3$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.3$ $h = 10^{-3}$

Figure 5a : 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: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 6$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.9$ $h = 10^{-3}$

Figure 5b : a) temperature evolution as function dimensional time; b) evolution of energy as function of for : $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 6$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.7$ $h = 10^{-3}$

Figure 5c : a) temperature evolution as function dimensional time; b) evolution of energy as function of for : $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 6$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.3$ $h = 10^{-3}$

Figure 6a: a) temperature evolution as function dimensional time; b) evolution of energy as function of for : $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 10$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.7$ $h = 10^{-3}$

Figure 6b: 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: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 10$, $\delta_\gamma = 0.9$, $\gamma_c = 0.4$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.3$ $h = 10^{-3}$

Figure 7a: 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: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 25$, $\delta_\gamma = 90$, $\gamma_c = 40$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.9$ $h = 10^{-3}$

Figure 7b: 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: $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 25$, $\delta_\gamma = 90$, $\gamma_c = 40$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.7$ $h = 10^{-3}$

Figure 7c: a) temperature evolution as function dimensional time; b) evolution of energy as function of for : $\rho = 2300$, $C_p = 505$, $\lambda = 2.7$, $k = 25$, $\delta_\gamma = 90$, $\gamma_c = 40$, $F_0 = 1$, $\alpha = 10^{-9}$ $\omega = 0.3$ $h = 10^{-3}$