An approach to earthquake prediction due to mantle flow and crust interaction

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Abstract

We are going to predict location, magnitude and time of an earthquake before shock as a complex adaptive system. In the Earth's equilibration and adaptation of the system, earthquakes and changes in material properties occur. We are going to model this process in the Earth. In other words, our approach is based on the Pulsating Mantle hypothesis, PMH, of authors as a methodology that says: "Two phenomena that are deduced from the gravity forces between the Earth, Moon and the Sun, are: (1) dislocation of the inner core and (2) appearing the bulge(s) toward the Moon and the Sun in the interface of the outer core and the mantle." The Earth has a fluid dynamic nature including fluid-structure interactions in different geologic time scales. Due to transient fluid-thermo-mechanical loading that is deduced from the two above-mentioned phenomena, the mantle flow, continental drift, movement of the tectonic plates, faults movement and consequently an earthquake occur in the heart of the domain in the Earth that is the fault. In this proposed approach we use the Finite Element Method (FEM) as a tool.
Keywords: inner core's dislocation, outer core's bulge, "pulsating mantle" Hypothesis, constitutive model, transient fluid-thermo-mechanical loading, thermo-visco-elastoplastic behavior, earthquake and Jerk.

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1 Introduction

An earthquake is a complex system. In this system the study consists of problems that involve complex interactions among their constituent parts. Computation will be a central theme of our research since its inception. During the time, the whole complex adaptive system of the Earth that is in dynamic conditions adapts itself because it is self-organized. Earthquakes are one of the causes of the Earth adaptation. Here, the center of our domain is a fault and we are going to predict the Earth's crust behavior.

2 Pulsating mantle hypothesis in a glance

In this hypothesis our view to the Earth structure is that the Earth has a fluid dynamic nature including fluid-structure interactions in different geologic time scales. Two phenomena that are deduced from the gravity forces between the Earth, Moon and the Sun, are; 1- dislocation of the inner core [1–3] toward the Moon and the Sun, and 2- appearing the bulge(s) [4,5] toward the Moon and the Sun in the interface of the outer core and the mantle. See Figure 1. Pathways of the head of the bulges are two stress paths from inside of the Earth to the crust.

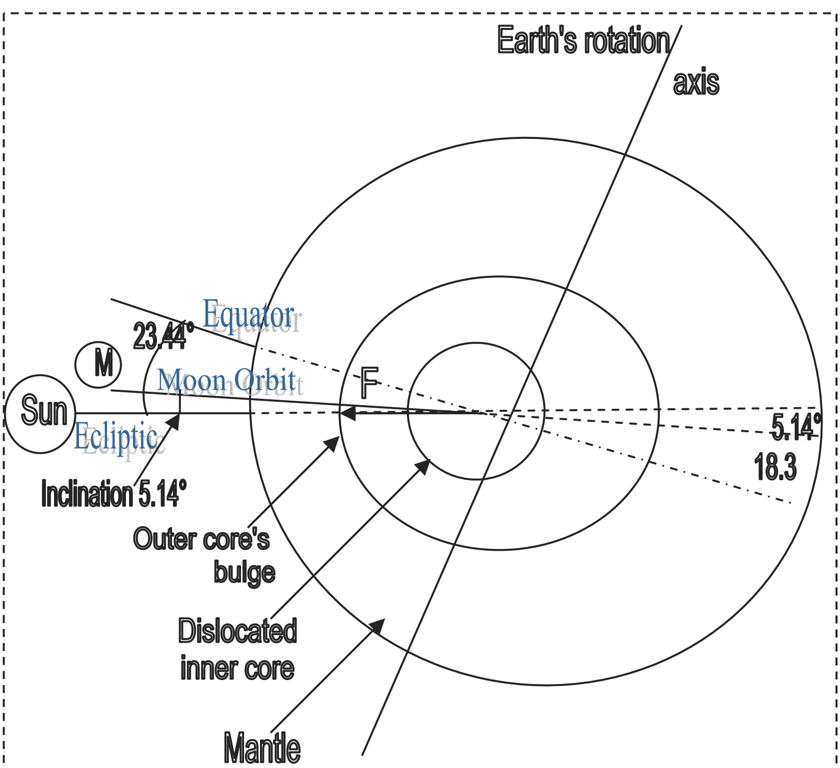

Figure 1: The situation of the planets and the earth's structure.

Due to the two above mentioned subjects the inner core is deformed [1,3], the outer core is formed like an egg and its top (bulge) acts as the main cause of the pressure (transient fluid-thermo-mechanical loading) to the bottom of the mantle from inside out the Earth, permanent changes in the boundary conditions of the interfaces between mantle and the bulge of the outer core appear and consequently the *pulsating mantle* hypothesis occurs in a regular diurnal cycle. Some results of the above mentioned phenomena are: occurrence of density jump, high shear velocity, high shear stresses, and shear heating in interaction zones (bulges) of the mantle-outer core [7], increasing turbulence in core flow [4,8,9], increasing in convection acceleration [5] and its effect into geomagnetic structure of the Earth [5], increasing in density and dynamic viscosity [10] in the bulge zone. Toward, up-down going of the flow [8,11] and consequently large buoyant mass in the Earth's outer core will be rapidly broken up into plate-like structures [8] and movement of the tectonic plates and continental drift. Arising as mountains, faults movements and earthquakes occurrence are the other results too. These two phenomena that appear in two diurnal cycles (during the diurnal rotation of the Earth) are the main cyclic loading from inside out the Earth and are causes of the many mechanical, physical and chemical changes within the Earth. These two diurnal cyclic loadings (two diurnal pulses that have two stress paths) from the outer core to the bottom of the mantle move the tectonic plates that transfer to the crust and produce earthquakes. During the eclipse these two loadings add to each other and make more heavy earthquakes and tsunamis. In this situation the loading for earthquakes is in its maximum magnitude. See Figure 2, correlation of the solar eclipse with the earthquakes is shown too.

3 Earth's structural mechanics

It was generally accepted that the Earth's solid interior behaved like a fluid on geologic time scales. The crust appears to float on a fluid mantle like blocks of wood float in water. This fluid behavior of the mantle on long time scales contrasts with the elastic behavior of the mantle on short time scales.

Then the lithosphere plates move relative to one another and cause stress to accumulate around faults until the frictional strength of the fault is exceeded and then the faults will rupture (fault behavior) and earthquakes occur. In other words, the plates move away from (divert) like the mid-Atlantic Ridge, move toward (convergent) like the west margin of the South American continent and slide past each other (transform plate boundaries) like the San Andreas fault where the Pacific plate slides past the North American Plate. In the other words, due to the Earth's crust cinematic movement that is an adequately mechanical phenomenon, the waves are produced and the fault acts as a damper. In this way the domain is fluid and then becomes solid. The Earth's internal mechanics is the cause of the Earth's crust movement and consequently earthquakes. The flow chart of the Earth's structural system behavior is depicted in Figure 3.

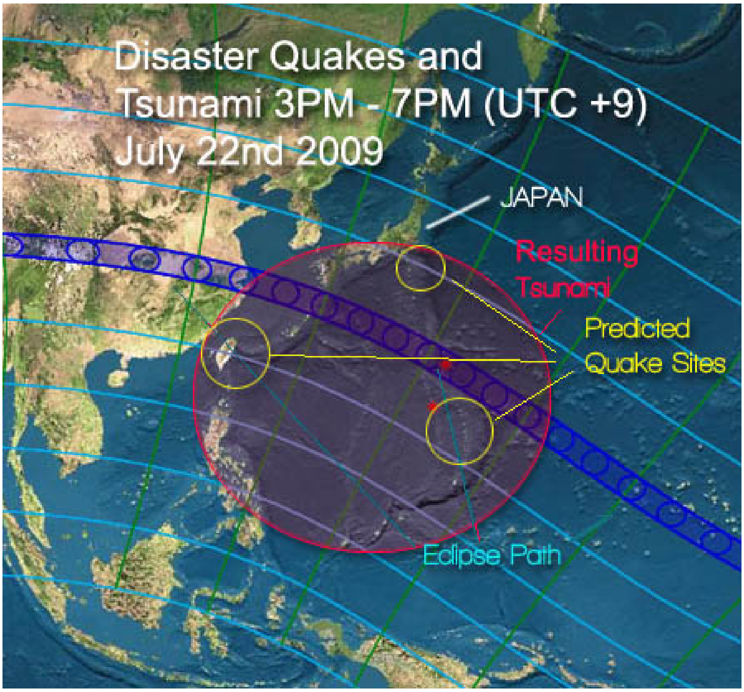

Figure 2: The blue double line (eclipse path) is the simultaneously two stress.

4 Earthquake mechanism

Earthquakes are necessary for the Earth's dynamics equilibrium and the faults act as local dampers in this process and help to the adaptation of the Earth's complex system. The mechanism of the changes in earthquake is the "jerk" phenomena that its formula is proposed by the authors as follows:

$$\{H\} = [J]\{\dddot{\delta}\} \tag{1}$$

in which $[J]$= jerk matrix (material properties of the fault zone) and $\{\dddot{\delta}\} = \dfrac{\partial^3 \delta}{\partial t^3}$ is acceleration rate matrix. This mechanism is like an axial compression test for rock sample in the Lab.

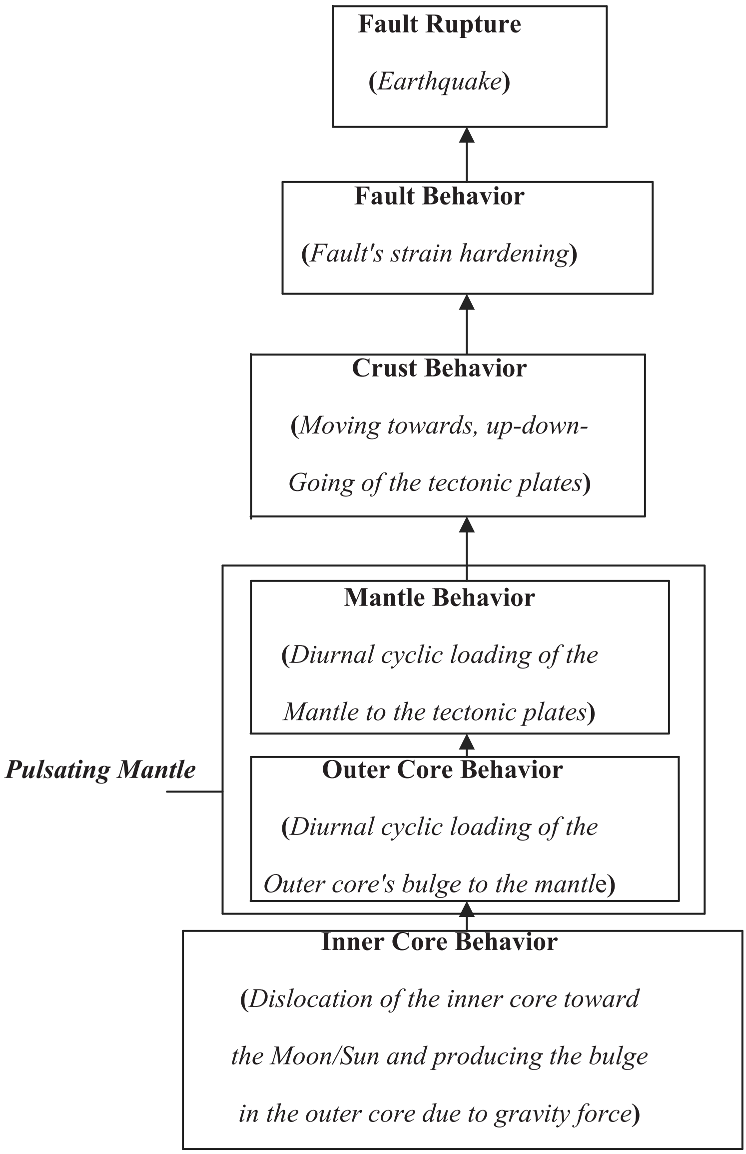

Figure 3: Flow chart of the earth's structural system behavior.

5 Computational approach

In complex adaptive systems study of problems involve complex interactions among inception. Here we use Finite Element Method (FEM) to resolve the problem.

5.1 Governing equations

The constitutive governing equation for the Earth's structural system behavior that is proposed by the authors is as follows:

$$[J]\{\dddot{\delta}\}+[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+[K]\{\delta\}=F(t) \tag{2}$$

in which $[M]$ is mass matrix, $[C]$ is damping matrix, $[K]$ is stiffness matrix, $\{\ddot{\delta}\}$ is acceleration matrix, $\{\dot{\delta}\}$ is velocity matrix, and $\{\delta\}$ is displacement matrix.

$$[J]=\begin{bmatrix} J_f & J_t & J_m & J_I \\ J_t & J_m & J_f & J_I \\ J_m & J_f & J_t & J_I \end{bmatrix}, \quad [C]=\begin{bmatrix} C_f & C_t & C_m & C_I \\ C_t & C_m & C_f & C_I \\ C_m & C_f & C_t & C_I \end{bmatrix}$$

$$[M]=\begin{bmatrix} M_f & M_t & M_m & M_I \\ M_t & M_m & M_f & M_I \\ M_m & M_f & M_t & M_I \end{bmatrix}, [K]=\begin{bmatrix} K_f & K_t & K_m & K_I \\ K_t & K_m & K_f & K_I \\ K_m & K_f & K_t & K_I \end{bmatrix}$$

$$\{\dddot{\delta}\}=\begin{bmatrix} \dddot{\delta}_f & \dddot{\delta}_t & \dddot{\delta}_m \\ \dddot{\delta}_t & \dddot{\delta}_m & \dddot{\delta}_f \\ \dddot{\delta}_m & \dddot{\delta}_f & \dddot{\delta}_t \\ \dddot{\delta}_I & \dddot{\delta}_I & \dddot{\delta}_I \end{bmatrix}, \quad \{\ddot{\delta}\}=\begin{Bmatrix} \ddot{\delta}_f & \ddot{\delta}_t & \ddot{\delta}_m \\ \ddot{\delta}_t & \ddot{\delta}_m & \ddot{\delta}_f \\ \ddot{\delta}_m & \ddot{\delta}_f & \ddot{\delta}_t \\ \ddot{\delta}_I & \ddot{\delta}_I & \ddot{\delta}_I \end{Bmatrix},$$

$$\{\dot{\delta}\}=\begin{Bmatrix} \dot{\delta}_f & \dot{\delta}_t & \dot{\delta}_m \\ \dot{\delta}_t & \dot{\delta}_m & \dot{\delta}_f \\ \dot{\delta}_m & \dot{\delta}_f & \dot{\delta}_t \\ \dot{\delta}_I & \dot{\delta}_I & \dot{\delta}_I \end{Bmatrix}, \quad \{\delta\}=\begin{Bmatrix} \delta_f & \delta_t & \delta_m \\ \delta_t & \delta_m & \delta_f \\ \delta_m & \delta_f & \delta_t \\ \delta_I & \delta_I & \delta_I \end{Bmatrix} \tag{3}$$

in which subscripts *f, t, m* are fluid, thermal, and mechanical and t in $F(t)$ is time and depends on to the viscosity, density, velocity, pressure, temperature and the time parameters and I is interaction between fluid, thermal and mechanical.

5.2 Constitutive model

This *Constitutive Model* [12] can analyze the thermal and mechanical behaviors simultaneously together in one process that it is ignored in the *superposition* method.

It is assumed that the yield function of Von Mises developed *Model* criterion is influenced (or hardening-softening) by the following causes: (a)-Plastic strain and its derivatives, (b)-Temperature, (c)- Fatigue and creep or (d)- Changes of properties by time like erosion and (e)- Microstructure changes like corrosion. Therefore the proposed yield function becomes:

$$F = f(I_1, J_2, T) \tag{4}$$

Or

$$F = J_2 - \frac{\sigma_0^2}{3}\left[1 + h_p \bar{\varepsilon}^p - \alpha\left(\frac{T - T_0}{T_m - T_0}\right)^\beta\right]^2 = 0 \tag{5}$$

in which whereby $\varepsilon = \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}_p : \dot{\varepsilon}_p}$, *K=K (T)*, *I1* = first invariant of the deviatory stress, J_2 = second invariant of deviatory stress including residual stresses, T = body temperature, T_m = melt point temperature, T_o = initial temperature of the body, α and β = parameters of the *Model*, h_p = hardening parameter, and σ_0 = initial (residual) stress.

In this *new Model* the yield surface will changes in the form of nonlinear with plastic strain and nonlinear with temperature (*T*), and in plastic deformation changing we have used associated flow rule. See Figure 4.

5.3 Computational procedure of the back analyses for the earthquake prediction

In this approach we are going to gain at least 3 curvatures of the fault's behavior for finding approximate curvature between them. Each curvature is behavior of the fault between two sequence earthquakes (our focus is on 4.5<E<6.2 Richter). The analysis for duration between two sequence earthquakes has 9 increments with 6 iterations in each. Number of increments depends on the duration between two sequence earthquakes in the specific fault.

5.3.1 Analysis for the first increment:

For the domain (specific fault), the analysis steps are: *Initial State*- After an earthquake and releasing the energy in the fault, the initial state is as follows:

$$\sigma = 0, \varepsilon = 0, t = 0, W = 0 \tag{6}$$

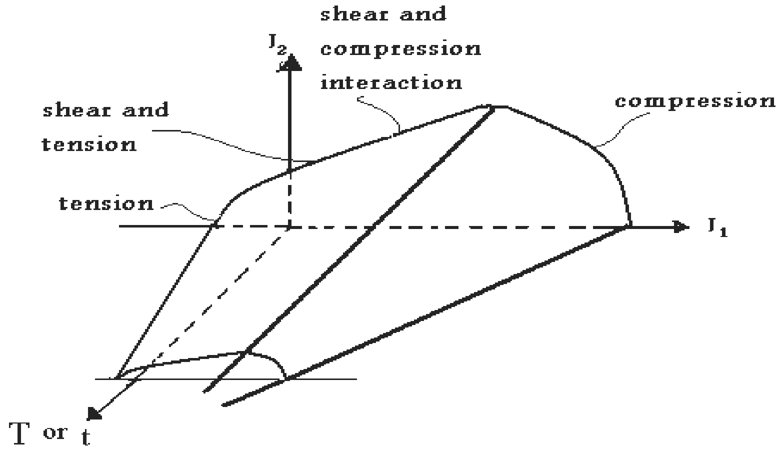

Figure 4: Yield surface of the model in 3D.

Step 1: After the first earthquake in the fault from bellow formula that is proposed based on *Pulsating Mantle* Hypothesis by the authors, we can find the strain energy *(W)* for a cycle (day) for the fault.

$$E = N.W \tag{7}$$

in which: *E*= released energy of the earthquake, *N*= number of the cycles (days) between two sequence earthquake in a specific fault and *W*= strain energy for each cycle (in one day) in a domain due to cyclic fluid-thermo-mechanical loading the outer core bulge to the mantle's bottom in a day. The released energy magnitude of the earthquake and duration between two sequence earthquakes are known.

Step 2: Here we should find experimentally (e.g. using strain gage) the thermo-visco-elasto-plastic strain, $\Delta\varepsilon$, in different depth of the specific fault (in the problem's domain) for each time step. Strain in matrix is proposed by the authors as follows:

$$\{\Delta\varepsilon\} = \begin{Bmatrix} \Delta\varepsilon_f \Delta\varepsilon_t \Delta\varepsilon_m \\ \Delta\varepsilon_t \Delta\varepsilon_m \Delta\varepsilon_f \\ \Delta\varepsilon_m \Delta\varepsilon_f \Delta\varepsilon_t \\ \Delta\varepsilon_I \Delta\varepsilon_I \Delta\varepsilon_I \end{Bmatrix} \tag{8}$$

in which $\Delta\varepsilon_f$ = incremental strain due to hydraulic loading, $\Delta\varepsilon_t$ = incremental strain due to thermal loading, $\Delta\varepsilon_m$ = incremental strain due to mechanical loading, $\Delta\varepsilon_I$ = incremental strain due to interaction between fluid, thermal and mechanical loading.

Step 3: Substituting *W* from equation (7), the strain from step 2, and constitutive equation in equation (9), consequently we can find the stresses (loading) for specific fault. This stress that is very important item in our analyses is diurnal loading magnitude from inside out to the crust.

$$W = \oint_v \Delta\sigma \cdot \Delta\varepsilon \cdot D_{ftm}^{tvep} \cdot dv \qquad (9)$$

in which $\Delta\sigma$ =incremental fluid-thermo-mechanical stress including the residual stresses, σ_0 , and in matrix form becomes as follows:

$$\{\Delta\sigma\} = \begin{Bmatrix} \Delta\sigma_f \\ \Delta\sigma_t \\ \Delta\sigma_m \end{Bmatrix} \qquad (10)$$

$\Delta\sigma_f$ = incremental fluid (hydraulic) stress, $\Delta\sigma_t$ = incremental thermal stress, $\Delta\sigma_m$ = incremental mechanical stress, *v*= volume of the domain, and D_{ftm}^{tvep} = constitutive equation or material properties of the specific fault for thermo-visco-elasto-plastic behavior of domain due to fluid-thermo-mechanical loading including a new interaction item, D_I, that is proposed by the authors. Its formula is proposed by the authors as follows:

$$D_{ftm}^{tvep} = \begin{bmatrix} D_f D_t D_m D_I \\ D_t D_m D_f D_I \\ D_m D_f D_t D_I \end{bmatrix} \qquad (11)$$

in which D_t = constitutive equation due to thermal loading, D_m =constitutive equation due to mechanical loading, D_I =constitutive equation due to interaction between thermal and mechanical loading.

5.3.2 Analysis for the second increment

Step 4: The new stress is the stress that we found in stage 3 plus residual stress from constitutive *Model* (equation 5), (σ_0 = initial (residual) stress) is as follows:

$$\Delta\sigma = \Delta\sigma + \sigma_0 \tag{12}$$

Step 5: For new strain, we should add an incremental strain (from strain guage variation during a time step) to the before strain (step 2). Now we do back analysis and get the *W2* by substituting the new stress and new strain in equation (9).

Step 6: By substituting *W2* in equation (7) we can get the *E2*. This is our prediction but we don't know its time yet. In the next real earthquake in the fault we can see its magnitude and its time and then by usage of its curvature we can define the time of our prediction (*E2*) and modified it. We can continue this analysis procedure for four times and get an approximate discipline for the fault behavior

5.3.3 Analyses for other increments

In schematic behavior of the fault, an approximation curvature for definition of the fault discipline is depicted in Figure 5.

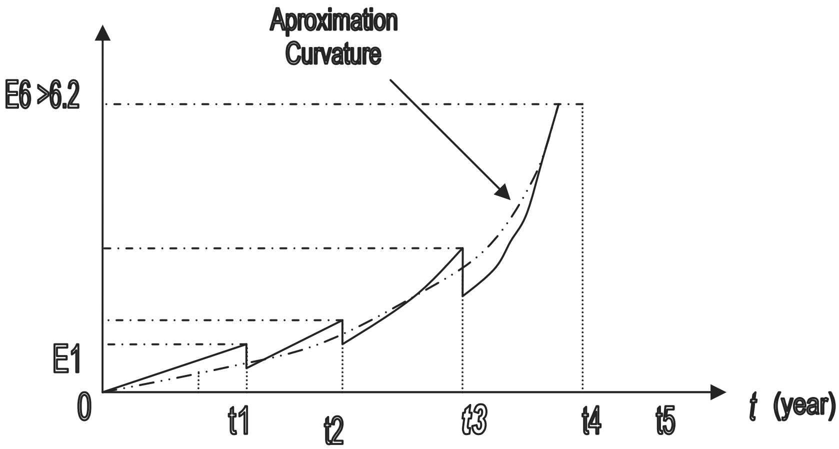

Figure 5: Behavior of the fault in 4 increments between 2 earthquakes.

6 Conclusion

Earthquakes are a dangerous reality for cities and civil projects. Analysis and computers are real source of progress of technology too. We can and must predict the behavior of the Earth in earthquake time by modeling of the Earth and usage of the constitutive models. For this goal we must model the crust behavior before earthquake and show numerically the earthquake phenomena and its causes. Idealization of the Earth's structure, magma and outer gravity forces like the Sun and the Moon gravity are the causes of the crust behavior. Consequently the crust's internal fluid and external loading are the earthquake causes. In this research that is on the base of the *Pulsating Mantle* Hypothesis, we can put the causes and effects in a computational procedure and predict the earthquakes and the Earth's behavior.

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