Principles of lithospheric plates movements and earthquakes triggering (shortened version)

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Abstract

Paper presents reasons why sometimes Full or New Moons correlate with earthquakes and sometimes not. Solution follows from calculations of tidal torques, dependent on Moon and Sun declinations, and their subtraction or addition gives resultant torques, able or unable to trigger earthquakes. To avoid usual objection, that if tidal torque act on the whole bulge, then we would expect periodicity in the movement of the plates related to the orbit of the Moon around the Earth and earthquakes should be happening very regularly at fixed periodicity, what is not allegedly observed. For this reason, I present consequent earthquake triggering from Mantawai Fault in Sumatra, Palu-Koro Fault in Sulawesi and San Andrea Fault in California happening shortly one after in fall and winter 2004. Position of earthquake on length of day (LOD) graph presents tool for earthquake origin.

Introduction

Attempts have been made to prove tidal relationship to earthquake triggering. Statistical attempts are unconvincing and in many cases present insignificant results. Let us mention positive results from Schuster 1897, Emter 1997, Heaton 1975, Cochran et al. 2004, Métevier et al. 2009, Tanaka 2010, 2012 and Chen et al. 2012a,b. Any correlation between tides and seismic activity reject Yung and Zũrn 1997, Vidale et al 1998, Stein 2004 and Tormann et al. 2015. First at all it is necessary to prove that tides are sufficient not only to trigger earthquakes but that they are able to move plates.

Calculation of tidal forces

To solve this problem let us calculate tidal forces, which act on plates. These forces are: 1. Forces, which try to align the Earth's flattening to the level of acting tidal forces, i.e. to the planes of Moon and Sun orbits. 2. Force, which brakes the Earth's rotation, i.e., the tidal friction.

1. Fig. 1 shows the action of the tidal force in its most effective action during the Sumatra earthquake 2004. The torque acting on the plate can be calculated in following steps (Brož et al 2012):

Earth's angular velocity $\omega = 7.29\ 10^{-5}$ rad/sec, Earth's moment of inertia $I = 8.07\times 10^{37}$ kg m^2 (Stacey, 1977). Earth's angular momentum $L = I\times\omega = 5.89\times10^{33}$ kg m^{2}s^{-1}. Mass of the lithospheric bulge is

$$m_{bulge} = \frac{1}{2}\left(\frac{4}{3}\pi abc - \frac{4}{3}\pi c^3\right)\rho_{crust},$$

where we insert a = b = R_e ≈ 6378 km, c = R – 21 km, ρ_{crust} ≈ 2700 kg m^{-3} and we get m_{bulge} ≈ 9.6 ×10^{21} kg ≈ 1/624 m_e . (Earth's mass m_e = 5.9 x 10^{24} kg). The torque of force couple acting on the Earth is then: in case of the Sun (m_s, r_s Sun's mass and distance, *G* gravitational constant)

$$M_s = 2 \times \frac{2Gm_{bulge}m_s}{r_s^3} R_e \cos\varepsilon . R_e \sin\varepsilon, \qquad (1)$$

where ε = 23.45° is the obliquity of ecliptic to equator. This is valid only in case if the mass of bulge were concentrated in one point on equator and the Sun were just in highest point above equator. In reality we should integrate over the bulge because some its parts are closer to the axis of rotation and to center over the Earth's rotation because the instant angle of the Sun above equator varies. We would get:

$$\overline{M}_s = \frac{1}{4} M_s \approx 5.7 \times 10^{21} \text{ N m}$$

The same calculation is for the Moon:

$$M_m = 2 \times \frac{2Gm_{bulge}m_m}{r_m^3} R_e \cos\iota . R_e \sin\iota, \qquad (2)$$

where ι is the Moon's declination. The result is $\overline{M}_m = \frac{1}{4} M_m \approx 1.2 \times 10^{22}$ N m. The torques simply summarize $\overline{M} = \overline{M}_s + \overline{M}_m = 1.8 \times 10^{22}$ N m.

This important result calculates that the torque 1.8 × 10^{22} N m is able to move the plate. The seismic moment of the Sumatra earthquake is 3.5 × 10^{22} N m (Varga and Denis 2010; Lay et al 2005; Stein and Okal, 2005). Because the torque exerted by tidal force acting on Earth's flattening represents the kinetic energy and also the seismic moment represents energy according to definition M_0 = μAD, where μ is the shear modulus N/m^2, D is displacement on area A, this quantity of N m dimension represents also energy, both quantities can be compared.

The tidal fiction decelerates the Earth's rotation (Lambeck, 1977) and therefore it can be also considered as the force causing the westward movement of plates (Ostřihanský 2012a, 2012b, 2012c). The torque exerted by the tidal friction is relative low 10^{16} N m. (Burša 1987a) and considering the mantle viscosity only 2 orders of magnitude lower than the lithosphere (Cathles 1975), this force is considered as insufficient for the plate movement.

2. The torques of tidal friction were calculated by Burša (1987a), (1987b) on the basis of angular momentum balance in the Earth – Moon – Sun system.

$$N_m = 4.2 \times 10^{35} \text{ kg m}^2 \text{ cy}^{-2} = 4.2 \times 10^{16} \text{ kg m}^2 \text{ s}^{-2} = 4.2 \times 10^{16} \text{ Nm}$$

$$N_s = 8.9 \times 10^{34} \text{ kg m}^2 \text{ cy}^{-2} = 8.9 \times 10^{15} \text{ kg m}^2 \text{ s}^{-2} = 8.9 \times 10^{15} \text{ Nm}$$

The ratio of tidal torques of Moon and Sun therefore is

$$N_m/N_s = 4.7$$

According to Jeffreys this ratio is 4.9 (Jeffreys 1975). The Sun's share in tidal friction is only 21%.

Mutual position of tidal forces

Now, it is necessary to realize when and why these forces act: To drive plates, plates should be released and this release is manifested by dropping down by gravity to mantle. Because at present time subduction zones were created only on the northern part of lithospheric plates, plates move northward. But tidal friction drives plates westward, supposing of course that they have subduction zone on their western side.

Complicated situations are created not only in Sun and Moon action in different mutual hour angles, but also in their action during diurnal cycle in New or Full Moons (Table).

	Phase	Moon Declination	**0 h**	**12.4 h**
Summer **S>0**	**Full** Moon	+	$+M - S_c$	$-M_c + S$
		-	$-M - S_c$	$+M_c + S$
	New Moon	+	$+M + S$	$-M_c - S_c$
		-	$-M + S$	$+M_c - S_c$
Winter **S<0**	**Full Moon**	+	$+M + S_c$	$-M_c - S$
		-	$-M + S_c$	$+M_c - S$
	New Moon	+	$+M - S$	$-M_c + S_c$
		-	$-M - S$	$+M_c + S_c$
Spring **S=0**		+	+M	-M
		-	-M	+M
Fall **S=0**		+	+M	-M
		-	-M	+M

Table shows possibilities of earthquakes triggering during Full or New Moon and in summer and winter time. Example: In winter and in Full Moon the torques of Moon and Sun are added as shown in rectangle with bold contours. Similar situation is in New Moon, Moon and Sun torques are negative but earthquake triggering occurs for 12.4 hours later. M and S are Moon and Sun torques proportional to Moon and Sun declinations, M_c or S_c are Moon and Sun counterparts. Following figures present explanation.

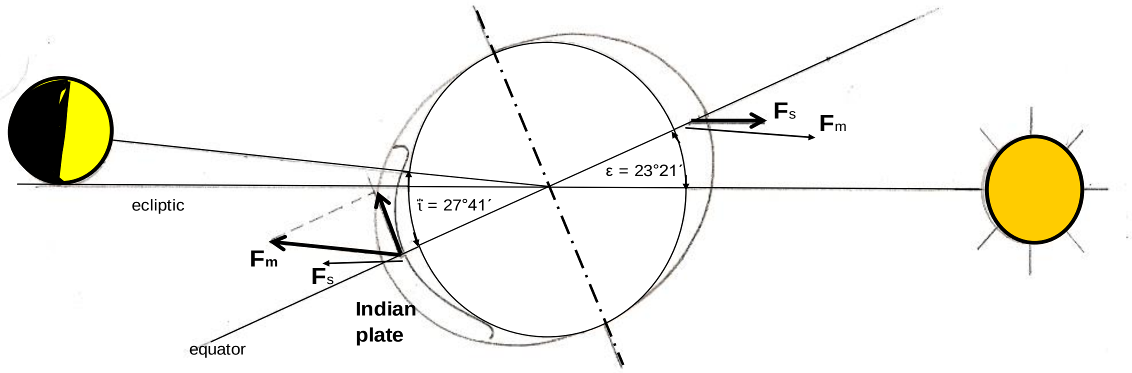

Figure 1 shows Full Moon, maximum Moon's declination 27º 21´ and the torque acting on Indian plate directs northward. 12.4 hours later torques direct southward (not marked in figure) against mid ocean ridge and no earthquakes are triggered. This is the case of Great Sumatra earthquake 2004. Moon's torque (F_m =M) directs northward and also the Sun's counterpart S_c=F_s), as evident in wintertime.

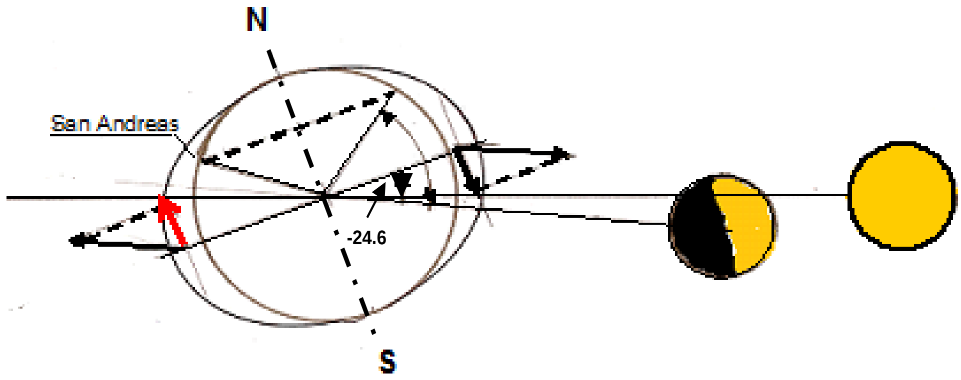

Figure 2. Case of New Moon in winter, when Sun's and Moon's declinations are negative (Moon –24.15º), but earthquakes are triggered for 24.4 hours later (marked by red arrow). Black arrow direct southward against mid-ocean ridge without any earthquake or the plate movement.

There are questions whether Full or New Moon trigger earthquakes. Statistics of Van der Elst at all. (2016) confirm it, but Hough, (2018) not. Looking at Table, it is evident that not all Full or New Moons have sufficiently strong torques to trigger earthquakes. Probability is about 50 % because in summer and in winter there are only two possibilities of summarizing Moon and Sun torques (in bold contours), remaining possibilities Moon and Sun torques subtract.

Tidal friction acts on plates semi-diurnally and westerly with very weak torque 10^{16} Nm as calculated. This can be considered as permanent action (similar as pressure of hand on drilling hammer) but drilling itself is performed by far stronger variations (electric or pneumatic device), in our case north-south tidal variations 10^{22} Nm. Load situated on inclined level surface, kept by friction but introduced into movement by strong variations, is a very good example of it. However lithospheric plate can move only if its front part is released by dropping down by gravity in subduction zone. Hawaii-Emperor Seamount chain has changed its direction owing to the change of position of subduction zone. All these examples are documented in author's paper (Ostřihanský 2015).

Consequent earthquake tidal triggering

To elucidate tidal action on earthquake triggering, let us consider three dominant faults on the Earth: Matawai Fault on Sumatra, Palu-Koro Fult on Sulawesi and San Andreas Fault in California (Fig. 3).

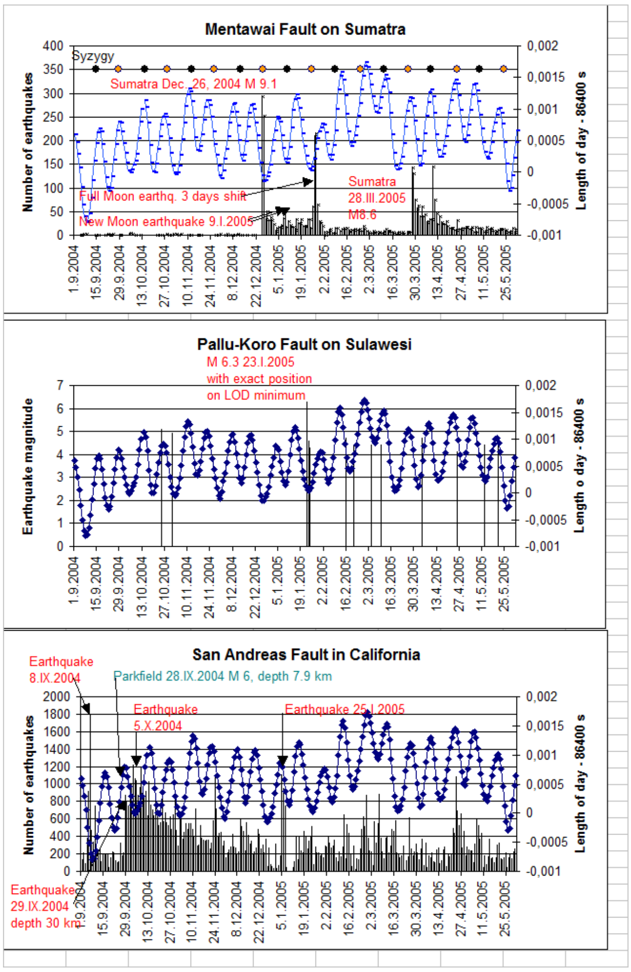

Figure 3. LOD graph and earthquakes during half-year from 1.IX.2004 to 31.V.2005. LOD maximums show dominantly Moon's 0º declinations, LOD minimums alternatingly positive and negative Moon's declinations. As evident, the reason for triggering of these three earthquakes was the Moon's high declination during the 18.6 years Moon's nutation cycle.

Great Sumatra earthquake is situated exactly in LOD minimum corresponding to extreme positive Moon's declination 27.9º and negative Sun's declination close to winter solstice -23º, forming the Full Moon configuration of maximum tidal torque. New Moon coincides with next LOD minimum 13.7 days later with Moon's negative –27.9º declination and almost unchanged Sun's negative declination (Fig 2) with maximum tidal torque at 12.4 hours later (the last bold contours rectangle of winter, (Table). The next LOD minimum is 23.I.2005 with 26.0º Moon's declination and the Full Moon in close position 25.I.2005. However the maximum earthquake does not correspond to LOD minimum, but is shifted for three days on position 27. and 28. I. 2005. The explanation is difficult; it is evident that only the third diurnal stroke triggered the earthquake.

Transferring our attention to the Palu-Koro Fault, it is evident (Fig.3) the earthquake 23.I.2005 corresponds to LOD minimum exactly, situated in 2000 km distance from Mentawai Fault in Sumatra. Whereas expressive LOD minimums on Sumatra and Sulawesi are empty of earthquakes (Fig. 3 left), the LOD minimum 8.IX.2004 on San Andreas Fault has earthquakes with aftershocks. Moon has maximum positive declination 27.8º. Low Sun's declination 5.4º in close position to autumn equinox and Moon in last quarter minimizes any influence of Sun.

Maximum westward tidal drags occur in Moon and Sun position on equator at 0º declination, i.e. in LOD maximums. Earthquakes increment occurred in San Andreas Fault 29.IX.2004 coinciding exactly with LOD maximum 29.IX.2004 (Fig. 3) with Moon's declination 6.4º and Sun's declination –2.6º. Next earthquake increment occurred in LOD minimum 5.X.2004 with declination 28.0º, corresponding to tidal north-south variation and further earthquake increment occurred till the end of December. The westward movement of the American plate is confirmed by earthquake one day before 28.IX.2004 at depth only 7.9 km, whereas earthquakes on Fig. 3 of San Andreas Fault occur in average depth 30 km. The next LOD maximum occurred 3.I.2005, but earthquake increment occurred for 2 days later 5.I.2005.

These earthquake-triggering delays are very common in LOD maximums and detailed investigation of earthquake Sumatra M 8.6 28.III.2005 shows the tidal origin of these earthquakes.

In this example the mechanism of tidal earthquakes triggering is well evident. North-south movement along Mentawai Fault and the great drop along subduction zone with tsunami manifest the Grear Sumatra earthquake M 9.1 26.XII.2004. For three months later the released Indian plate moved westward overriding subduction zone but without tsunami.

It is difficult to explain why the Sumatran earthquake of New Moon 10.I.2005 was triggered exactly in LOD minimum and minimum declination –27.9º but earthquake in San Andreas Fault 11.I.2008 at 4 days delay as Fig. 4 depicts. In San Andreas Fault case in New Moon configuration conditions existed in disturbed area of extreme earthquake 26.XI.2004 of 9.1 magnitude. Before earthquake 11.I.2008 long quiet period existed and the earthquake was triggered only after the fourth diurnal stroke.

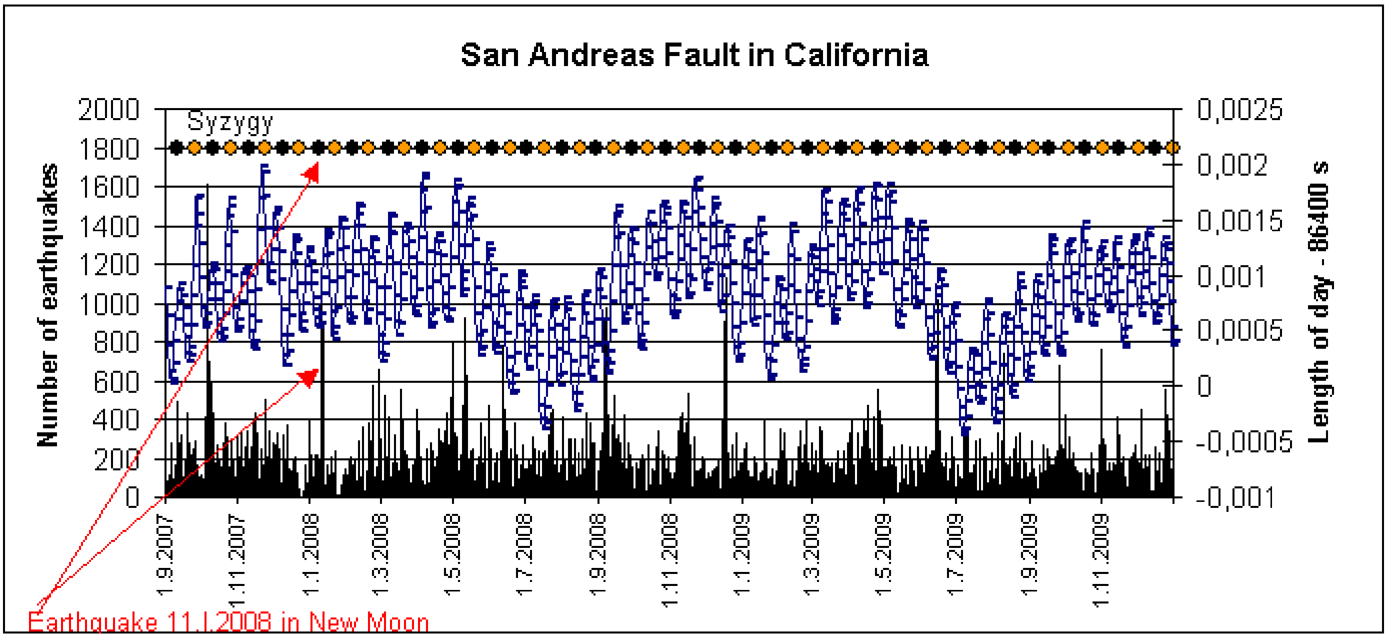

Figure 4 shows that coincidence of syzygies (Full or New Moon) with earthquakes are more likely extraordinary, as shows this shorter time span from IX. 2007 to XII. 2009. Only New Moon 11.I.2008 correlates with earthquake but with 3 days delay. More likely earthquakes correlate with LOD extremes, i.e. Moon's extreme declinations. However Van der Elst et al.

(2016) proved correlation with szyzgies for time span 2008 – 2015. Earthquakes positions are taken from 15 years Catalogue of Shelly (2017).

Figure 4 shows 57 syzygies and about 6 earthquake increments to 800 earthquakes/day. Only New Moon 11.I.2008 correlate with earthquakes increment with negative Moon and Sun declination according last row in Table for winter S<0.

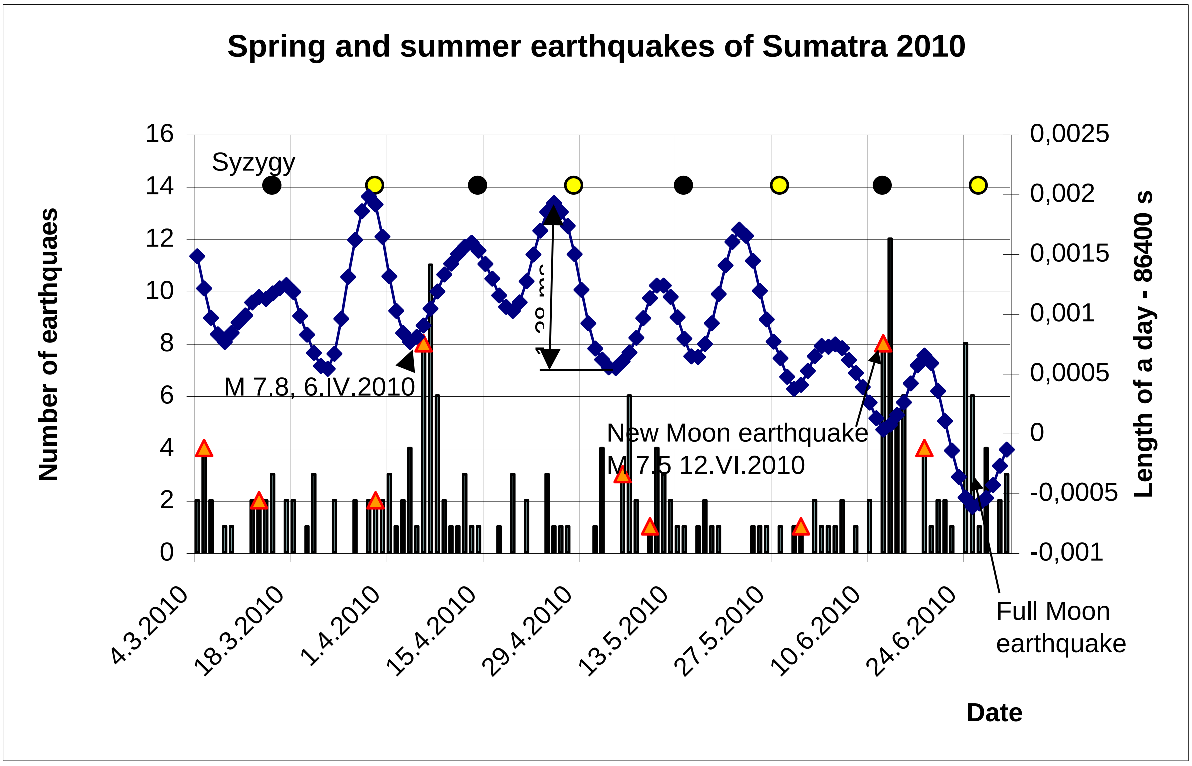

Figure 5. In contrast to New Moon earthquakes of Sumatra and San Andreas Fault triggered in winter time with negative declinations –27.9º and –27.5º (Figs. 3 and 4), the New Moon earthquake M 7.5 12.VI. 2010 has positive declination 25.0º, fully in agreement with Table for earthquakes in summer time because this earthquake was triggered 7 days before summer solstice. Spring earthquake M 7.6 6.IV.2010 in last quarter has declination –25.2º and was triggered 12.4 hours later according Table +M. Triangles mark earthquake over M 5.5.

Fig. 5 shows earthquake triggering during New Moon and Full Moon, where cooperation of Sun's torque is evident. In Moon's last quarter the Sun's torque is minimized also owing to minimum Sun's declination in vernal equinox, but Moon's torque itself is able to trigger earthquake.

Conclusion

Earthquakes are triggered during Full or New Moon owing to summarizing action of Moon and Sun torques but relatively scarcely. Mostly, Moon and Sun's torques are subtracted, what decreases probability of earthquakes triggering. Low declinations and from it Moon and Sun low torques also decreases probability of earthquakes triggering. However high tidal torque of Moon, without support of Sun, very often triggers earthquakes. Earthquakes are often triggered by tidal friction, which is manifested by 0º declination because at that time Moon acts along equator. If tidal friction occurs before or after Full or New Moon, under such conditions, earthquake occur minimally often without any earthquakes. :

Main factor influencing the Earth's behavior is the Earth's rotation axis inclination to the plane of Earth's orbit (obliquity) ±23.5º and also Earth's axis inclination to Moon's plane of orbit varying from ± 28°36′ to ± 18°20′. These values (declinations), inserted to formulas (1) and (2) give torques sufficient to move lithospheric plates and by their movement they trigger earthquakes. Let us mention that that Earth's axis is very stable by presence of Moon, as (Laskar et al. 1993) have shown, Moon's variation (nodal cycle) can predict earthquakes (Ostřihanský 2016a,b,c, 2017a), Earth's axis wobble the Milankovich cycles (Milankovich 1941) and of course the Earth's axis tilt creates year's seasons.

. Considering equilibrium tides, originally developed by Darwin (1879), it assumes that the gravitational potential of the tide raiser can be expressed as the sum of Legendre polynomials P_l . and the shape of a body can be well-represented by a superposition of surface waves with different frequencies and amplitudes. Calculations show semidiurnal uplift of Earth's surface ≈20 cm and related statistics present insignificant results of earthquake triggering with semidiurnal period, (Vidale et al., 1998). Statistics are also disturbed by earthquake delay for several days (in Fig. 4 for 3 days) and cumulative action of tidal friction and north-south tidal torque plus earthquake aftershocks stay earthquakes to unpredictable position.

Acknowledgments

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Length of day variations are taken from IERS (Earth rotation service) **http://hpiers.obspm.fr/eop-pc/** Moon and Sun declinations from Sun & Moon position Calculator on Internet, Moon phases from Internet. Earthquakes data for Sumatra and Sulawesi are taken from ANSS Catalog and EMSC Catalog. For California *A 15 year catalog of more than 1 million low-frequency earthquakes* was taken.

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