INFLUENCE OF THE EARTHQUAKES ON THE POLAR MOTION WITH EMPHASIS ON THE SUMATRA EVENT

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ABSTRACT. We compute the theoretical effects of the Earthquakes on polar motion from 1977 to nowadays. According to our estimates, the big Sumatra earthquake of December 26 2004 caused a polar shift below 3 cm. The polar motion observation cannot discriminate such a small amount from "normal" polar motion induced by atmosphere and oceans.

1. THE SUMATRA EARTHQUAKE

Whereas the influence of earthquakes on Earth rotation is a recurrent theme since the sixties, nothing has been ever observed. The gigantic Earthquake, that took place on 2004 December 26 at 00h 58min 51s UTC (modified Julian Date : 53365.041), about 200 km from the western coast of northern Sumatra (epicenter of latitude 3.298° and longitude 95.778°), has constituted an opportunity for recording a possible effect. Indeed its magnitude on the Richter scale reached at least $m = 9$, that makes it the third or forth biggest Earthquake ever recorded after those of Chile (1960, $m = 9.5$), Alaska (1964, $m = 9.2$), Kamchatka (1959, $m = 9$). The earthquake occurred as thrust-faulting on the interface of the India plate and the Burma microplate. In a period of minutes, the faulting released elastic strains that had accumulated for centuries from ongoing subduction of the India plate beneath the overriding Burma microplate. The ground over 1000 km fault was displaced in average by about 11 m (see Fig. 1). Probably as well excited as the Earth, some geophysicists, relieved by journalists, claimed in the following hours of the catastrophe, that a sudden polar shift had been observed. In the same time we began our investigation. We had already acquired some skill in this matter thanks to a cooperation carried out with the Seismologic Institute of Budapest (P. Varga, Z.Bus). In this paper, we shall present our own estimates of the polar wobble due to the Earthquake since 1977 with emphasis on the Sumatra event. Then, by analyzing polar motion observation, we shall attempt to answer whether the Sumatra effect has been detected or not.

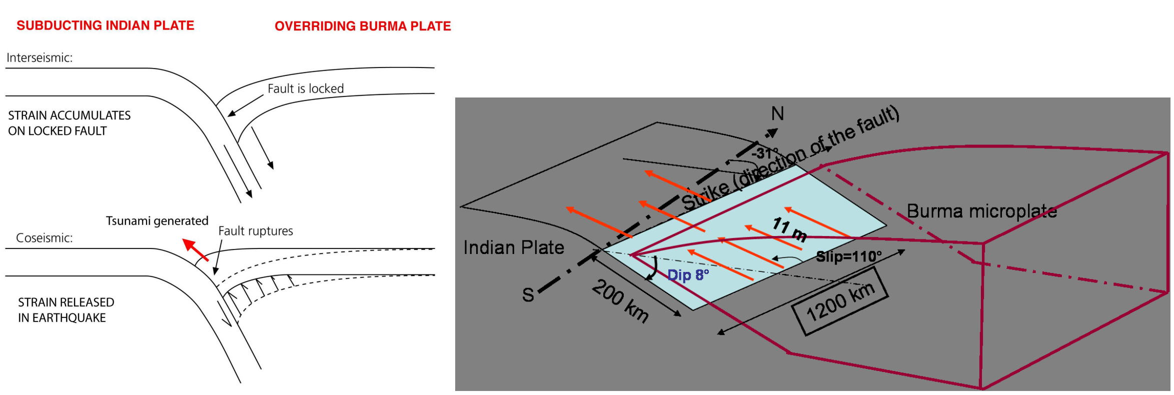

Figure 1: Left : subduction mechanism. Right : geometry of the ground displacement

2. BASIC EQUATION AND INERTIA INCREMENTS

When mass redistribution occurs inside the Earth, off-diagonal elements of the earth inertia matrix referred to the terrestrial frame $c_{13} = -\int_M xz\, dm$ and $c_{23} = -\int_M yz\, dm$ may change, as well as the equatorial relative angular momentum $h = h_1 + ih_2$. It follows that the Earth wobbles around the rotation axis in space, and from a terrestrial point of view the rotation axis moves with respect to the crust. For an elastic Earth model, the coordinates of the rotation axis $p = x - iy$ obey the Euler-Liouville equation :

$$p + i\frac{\dot{p}}{\sigma_C} = \frac{c}{(C-A)} + \frac{1.47h}{(C-A)\Omega} \tag{1}$$

where Ω is the mean Earth angular velocity, σ_C the Chandler pulsation ($\Omega/433$, $c = c_{13} + ic_{23}$, where C the axial inertia moment of the Earth, A the equatorial one. In the case of an earthquake, c can be modeled as a step function. The effect of relative angular momentum h is negligible, because it is not permanent. Then it can be easily shown that the consequence of the polar motion is a sudden offset of the pole, and a modification of the amplitude of the Chandler component according to :

$$\Delta p = \frac{c}{C-A} - \frac{c}{A}(\frac{\Omega}{\sigma_C} + 1)e^{i\sigma_C(t-t_0)} \tag{2}$$

We shall see that the inertia increment c can be deduced from seismic parameters. These ones are related to :1) the location of the epicenter : depth h, longitude Φ, colatitude θ) 2) the seismic displacement : it is modeled as uniform in a given plane, given by the northern azimuth α of its intersection with the earth surface (strike angle) and by its inclination with respect to the horizon δ ; the mean displacement itself is called the *slip* D, and the direction of the slip λ in this plane is reckoned from the strike direction 3) the area of the earthquake S. From the here above parameters seismologists define a quantity homogeneous to a moment of force, the seismic moment $M = \mu SD$ where μ is the shear modulus ($\approx 75Gpa$). This quantity combines the mean displacement and the surface which is concerned in relation with the shear force involved in the sliding. In Table 1 we report the seismic parameters for Sumatra Event (noted "Sum. Ev." in what follows), which are illustrated in Figure 1.

Center	Strike a	Dip angle D	Slip angle λ	Slip D	fault area S	Seismic moment M_0	Depth h
Harward CMT	329°	8°	110°	11 m	$\approx 105000km^2$	$4\,10^{22}$ Nm (up to 10^{23} Nm)	10 km
USGS	274°	13°	55°			$2.6\,10^{21}$ Nm	30 km

Table 1: Seismic parameter of the Sumatra Event

From elastic dislocation theory, Dahlen (1973) expressed the induced equatorial inertia moment increments in function of seismic parameters : seismic moment M_0, strike angle α, dip angle δ, slip angle λ, colatitude θ, longitude Φ :

$$\begin{aligned}
c_{13} = M_0\{ \quad & \Gamma_1(h) \quad [(\sin 2\alpha \sin\delta\cos\lambda + \tfrac{1}{2}\cos 2\alpha \sin 2\delta \sin\lambda)\sin 2\theta\cos\phi \\
& \qquad -2(\tfrac{1}{2}\sin 2\alpha\sin 2\delta\sin\lambda - \cos 2\alpha\sin\delta\cos\lambda)\sin\theta\sin\phi] \\
+ \; & \Gamma_2(h) \quad (-\sin 2\delta\sin\lambda\sin 2\theta\cos\phi) \\
+ \; & \Gamma_3(h) \quad [(\sin\alpha\cos 2\delta\sin\lambda - \cos\alpha\cos\delta\cos\lambda)\cos 2\theta\cos\phi \\
& \qquad +(\sin\alpha\cos\delta\cos\lambda + \cos\alpha\cos 2\delta\sin\lambda)\cos\theta\sin\phi]\} \\
c_{23} = M_0\{ \quad & \Gamma_1(h) \quad [(\sin 2\alpha\sin\delta\cos\lambda + \tfrac{1}{2}\cos 2\alpha\sin 2\delta\sin\lambda)\sin 2\theta \\
& \qquad +2(\tfrac{1}{2}\sin 2\alpha\sin 2\delta\sin\lambda - \cos 2\alpha\sin\delta\cos\lambda)\sin\theta\cos\phi] \\
+ \; & \Gamma_2(h) \quad (-\sin 2\delta\sin\lambda\sin 2\theta\sin\phi) \\
+ \; & \Gamma_3(h) \quad [(\sin\alpha\cos 2\delta\sin\lambda - \cos\alpha\cos\delta\cos\lambda)\cos 2\theta\sin\phi \\
& \qquad -(\sin\alpha\cos\delta\cos\lambda + \cos\alpha\cos 2\delta\sin\lambda)\cos\theta)\cos\phi]\}
\end{aligned} \tag{3}$$

Seismic parameters	Inertia moments 10^{26} kg m^2	Pole shift x (mas)	Pole shift $-y$ (mas)	
Harvard CMT	$c_{13} = -6.1$ $c_{23} = 0.76$	-0.68	0.09	2 cm 173° E
Hayward CMT*		-1.7	0.45	5 cm 165° E
USGS	$c_{13} = -0.47$ $c_{23} = 0.17$	-0.05	0.02	0.16 cm 160° E

* with 2.5 bigger seismic moment (Stein, Okal Nature,2005)

where $\Gamma_1(h)$, $\Gamma_2(h)$, $\Gamma_3(h)$ are function of the depth h. Without the need of considering these complicated expressions, it can be easily understood that in the case of equatorial Earthquake, the cartesian coordinate z of any mass element is closed to zero in the expression of c_{13} and c_{23}, and this make these quantities small. Therefore the very small latitude of Sumatra will preclude any large effect on polar motion. By using the Haward CMT catalogue, available on the WEB (www.seismology.harvard.edu), and giving the here-above parameters from 1977 to nowadays, we reconstituted the polar motion seismic excitation $\frac{c}{(C-A)}$. Its components in the terrestrial frame are depicted in Figure 2. Note the stability from 1964 to 1994, then the apparition of a slope these last ten years, amplified by the Sumatra earthquake. For Sumatra, the results of our

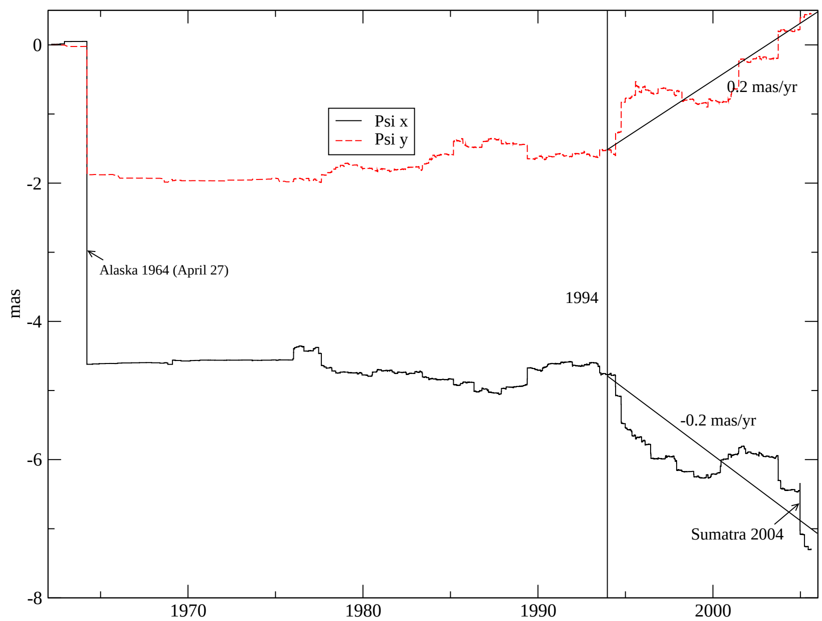

Figure 2: Co-seismic excitation of the polar motion from 1962 to 2005 (equivalently induced polar drift).

computation are reported in Table 2. The amplitude of the corresponding displacement of the rotation axis at the Earth surface varies from 0.2 cm up to 5 cm according to the estimates of the seismic moment towards $160 - 170°$ E, amount comparable to that one obtained by Gross and Chao (2005) (2.5 cm toward 145° E)

3. HAS SUMATRA EFFECT BEEN DETECTED ?

As comparison, the Alaska event (1964) of magnitude 9.2 has produced a shift of 15 cm according to the Dahlen model (see Fig. 3). With the modern techniques it would have been observed for sure, because such an displacement is much more important than the daily effect of the atmosphere and oceans, which reaches 3-9 cm per day. For the same reason, a shift of a few cm, like the one expect for Sum. Ev, is hardly detectable. Unless having hourly observations, classical daily determination of polar motion does not allow us to make difference between the

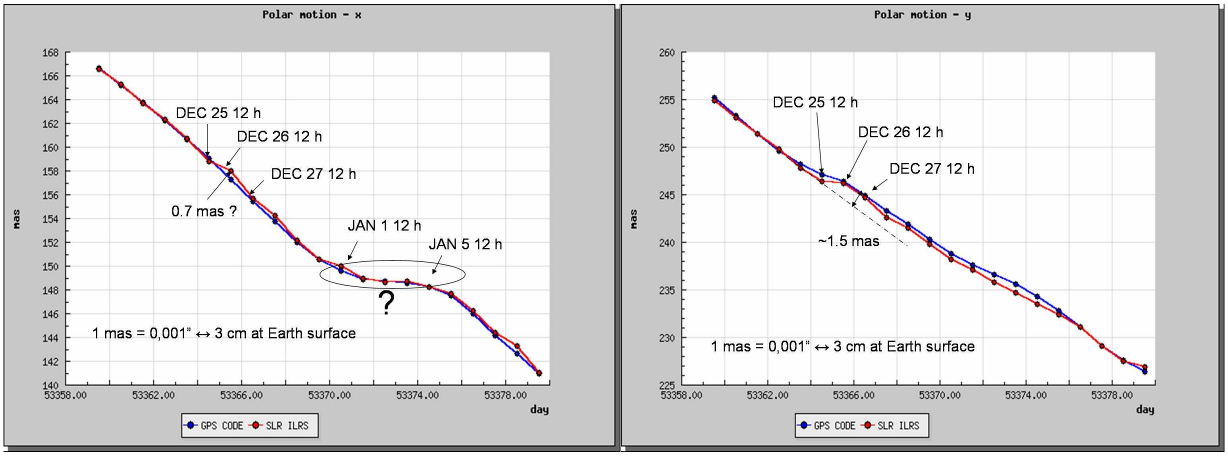

Figure 3: Polar motion around December 26. Satellite Laser Ranging Data and GPS (CODE) data slightly differ.

sudden seismic displacement and the habitual effect. Both are inextricably blended. The pole is slightly shifted (+0.7 mas for coordinate x, -1 mas for coordinate $-y$) from the 27th of December, as it appears the most clearly in SLR observations (see Fig. 3). But it cannot be taken as serious proof of Sumatra effect, as claimed by some of my colleagues. For essentially two reasons : 1) the observed effect is opposite to the theoretical estimate 2) centimeter shift in daily polar motion are routinely observed without any powerful earthquake taking place. For instance note the sudden stopping of pole according to the x axis from December 30th. To get the bottom of this problem, it is necessary to model the classical geophysical effects on the polar motion, and to isolate then the non explained part. For this period we have only at hand atmospheric data. The atmospheric excitation has been compared to the one found in polar motion. Around December 26th the difference between both function looks ordinary, not justifying any large episodic phenomena (larger than 10 mas). This analysis should be completed by the inclusion of oceanic angular momentum, unfortunately not yet available in public domain for December 2004. By the way the geophysical excitation is not accurately determined in order to deduced pure geodynamic excitation with the required accuracy level (0.5 mas at least!).

4. CONCLUSION

Sumatra Earthquake may have shifted the rotation axis at observable level ($2-3$ cm at the Earth surface in a few min), but such an effect is hardly distinguishable from common polar motion caused by the atmospheric/oceanic process ($6-15$ cm/day). The expected shift is for x axis, but what has been actually observed is a shift for y component (1.5 mas $\approx$ 4.5 cm). We shall conclude that Sumatra effect has not been observed. Another important conclusion of this study is that from 1964 to 1994 the excitation function is stable, but since 1994, it presents a significant drift towards 145°E, of about 0.2 mas/year (just above the accuracy level of the fit of the secular term in polar motion).

REFERENCES

Dahlen, 1973, “A correction to the Excitation of the Chandler Wobble by Earthquakes”, GJR, 32, 203-217.

Gross and Chao, 2005, “Excitation of Earth Rotation and Gravitational Field Changes by the December 26 Sumatran Earthquake”, Eos Trans. AGU, 86(18), Jt. Assem. Suppl., Abstract U52A-02