Variation of the Earth tide-seismicity compliance parameter during the recent seismic activity of Fthiotida, Greece

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Abstract

Based on the results of our studies for the tidal triggering effect on the seismicity of the Hellenic area, we consider the confidence level of earthquake occurrence - tidal period accordance as an index of tectonic stress criticality for earthquake occurrence and we check if the recent increase in the seismic activity at Fthiotida in Greek Mainland indicate faulting maturity for a stronger earthquake. In this paper we present the results of this test.

Key words: Earth tides, Seismicity, Hi(stogram)Cum(ulation) method

1. Introduction

Applying the Hi(stogram)Cum(ulation) method, which was introduced recently by Cadicheanu, van Ruymbecke and Zhu (2007), we analyze the series of the earthquakes occurred in the last 50 years in seismic active areas of Greece, i.e. the areas (a) of the Mygdonian Basin(Contadakis et al. 2007), (b) of the Ionian Islands (Contadakis et al. 2012), (c) of the Hellenic Arc (Vergos et al. 2012) and (d) Santorini (Contadakis et al. 2013). The result of the analysis for all the areas indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly and semi-monthly (Mm and Mf) variations and the same happens with the corresponding daily variations of the frequencies of earthquake occurrence with the diurnal luni-solar (K1) and semidiurnal lunar (M2) tidal variations. In addition the confidence level for the identification of such period accordance between earthquakes occurrence frequency and tidal periods varies with seismic activity, i.e. the higher confidence level corresponds to periods with stronger seismic activity. These results are in favor of a tidal triggering process on earthquakes when the stress in the focal area is near the critical level. Based on these results, we consider the confidence level of earthquake occurrence - tidal period accordance, p, as an index of tectonic stress criticality for earthquake occurrence and we call it **"Earth tide-seismicity compliance parameter".** Then we check on posterior if the variation of the confidence level index p, indicate the fault maturity in the case of the recent seismic activity at Fthiotida, Greece. In this paper we present the results of this test.

2. Seismicity in the broader area of Fthiotida

On August 7nth of 2013 a 5.2 M_L earthquake occurred in Fthiotida area followed by a seismic activity with shocks of magnitudes greater than 4.0 M_L which is continued until today. The area is a known tectonically active area in Greece. On 20 and 27 of April, 1894 two earthquakes of 6.4 and 6.6 M_L had more than 250 dead and hundreds of injured in human casualties and shattered thousands of houses.(Ganas et al. 2006, Papazachos et al. 2003). Figure 1 displays the area and the shocks with magnitudes greater than 2.5 M_L which occurred within 2013. In this figure the main faults of the area, as it is quoted by (Ganas et al. 2006), were drown. It is seen that the seismic activity of 2013 occurred in Kallidromon fault. It should be noted that the main faults of the area are normal, as it is happened with the faults of the broader area. Table 1 displays the earthquakes with magnitudes greater than 4 M_L occurred in the area within the year 2013.

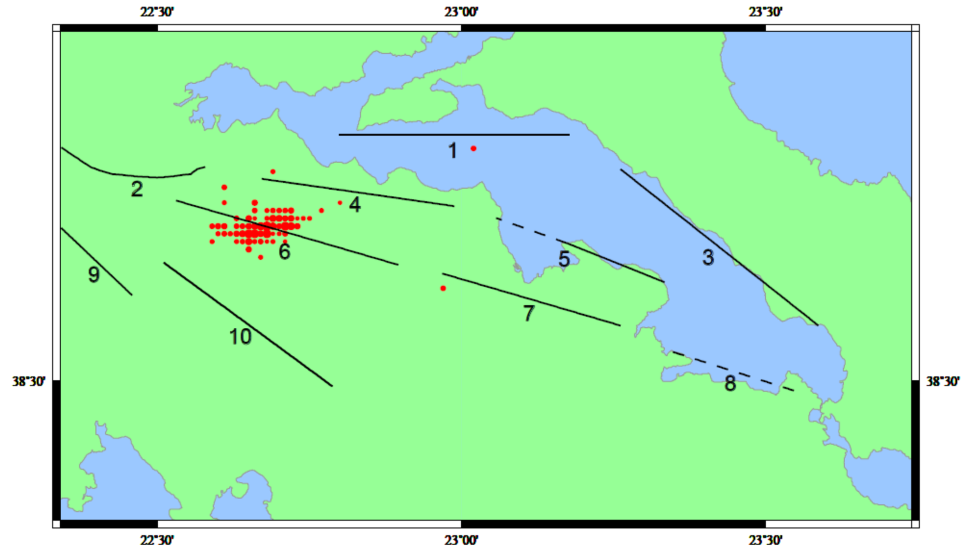

Figure 1. The seismic activity of 2013 in Fthiotida.(Shematic fault of the area(Ganas et al. 2006)).(1) Edipsos, (2) Sperchios, (3) Kadilli, (4,5) Kamena Vourla, (6) Kallidromon, (7,8) Atalanti, (9,10) Tithorea.

Table 1. Earthquakes with $M_L > 4.0$, Occurred in Fthiotida area in 2013

	Date	Time	Distance from the nearest city	φ degree	λ degree	Depth km	Magnitude
1	2013/12/11	13:00:53	17.4 km NW of Lamia	39.01	22.29	21	4.2
2	2013/11/22	15:12:03	16.8 km N of Lamia	39.05	22.41	21	4.2
3	2013/11/12	18:09:28	31.2 km NNE of Atalanti	38.92	23.10	17	4.8
4	2013/09/20	02:05:18	32.0 km NNE ofKorinthos	38.18	23.13	23	4.4
5	2013/09/17	07:39:44	24.0 km WNW of Atalanti	38.70	22.73	13	4.0
6	2013/09/16	15:01:14	23.8 km WNW of Atalanti	38.72	22.74	17	4.9
7	2013/09/16	14:42:39	24.0 km WNW of Atalanti	38.70	22.73	20	4.5
8	2013/08/18	16:39:21	24.8 km WNW of Atalanti	38.70	22.72	13	4.0
9	2013/08/18	10:42:54	24.8 km WNW of Atalanti	38.70	22.72	14	4.0
10	2013/08/09	13:10:10	30.0 km SE of Lamia	38.69	22.65	17	4.7
11	2013/08/09	11:49:56	28.0 km W of Atalanti	38.69	22.68	9	4.6
12	2013/08/09	11:49:23	25.7 km WNW of Atalanti	38.70	22.71	19	4.8
13	2013/08/07	13:44:32	29.8 km W of Atalanti	38.69	22.66	15	4.7
14	2013/08/07	09:56:35	27.4 km WNW of Atalanti	38.70	22.69	14	4.0
15	2013/08/07	09:06:51	28.2 km W of Atalanti	38.70	22.68	8	5.2
16	2013/08/07	09:02:45	29.1 km W of Atalanti	38.70	22.67	14	4.3
17	2013/04/28	04:49:55	14.7 km E of Aegion	38.26	22.25	55	4.2
18	2013/01/30	04:27:25	35.2 km ENE of Atalanti	38.78	23.37	22	4.0

In addition two strong earthquakes with magnitude 5,1 and 5.2 occurred in Aegion area on 18 and 20 of January,2010 and followed with enhanced micro-seismic activity ever since. It appears that the broader area of Fthiotida is in a sort of excitation with main focuses of Fthiotida and Aegion.

In our analysis we use the seismological data of the earthquake catalogue of NOA (http://www.gein.noa.gr). The set of data consist of a series of 33281 shallow and 769 of intermediate depth earthquakes with M_L ranging from 0.2 to 6.3, occurred within the time interval from January1964 to December 2013, in an area bounded by $38^o \leq \varphi \leq 39^o$ and $21^o\ 00' \leq \lambda \leq 23^o 30'$. Figure 2 displaces the development of the seismicity in the area from 1964. It is seen that the number of shocks is greatly increased since 2009.

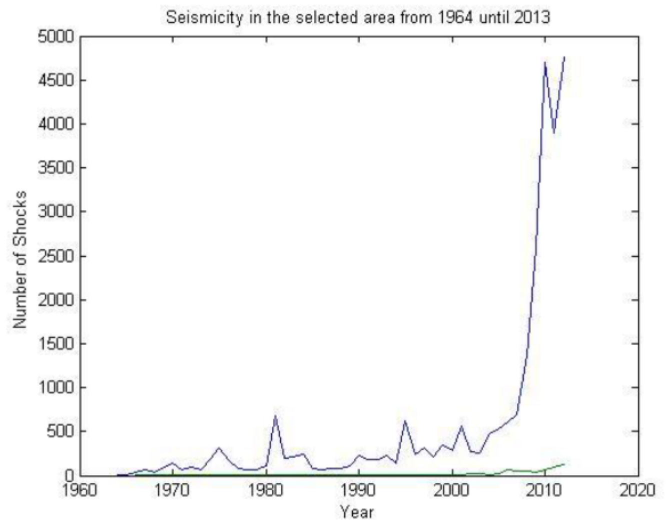

Figure 2. The development of the seismicity in the selected area from 1964 until2013. Green line indicate the number of the deep earthquakes.

3. Tidal effect

Tidal effects on a rigid Earth can be computed theoretically from the ephemerides of the Moon, the Sun and the planets. The Earth tides are the combined effect of the mentioned celestial bodies and the reaction of the solid Earth (like an elastic body) to the tidal forces. The ocean tides follow the law of hydrodynamics, with strong disturbances affecting adjacent seas, so that the ocean loading effect has to be taken into account. Earth tides are discussed extensively in Melchior (1983), Baker (1984), Wilhelm et al. (1997), Torge (2001).

The constituents of the Earth tides for the area of Thessaloniki were determined gravimetrically by Arabelos (2002). Table 3 displays the strongest components of the Earth tides for Thessaloniki. Although the amplitude of the lunar tidal component M1 is equal 27.091 nms^{-2} (see Arabelos, 2002, Table 3), i.e. it is much weaker than the listed components, we consider in addition the possible effect of this constituent by means of the lunar synodic month (i.e. period from new moon to new moon which is $29^d.530589$) as well as by lunar anomalistic month (i.e. time period between two successive passages of the moon from perigee which is $27^d.554551$).

Table 3. The strongest components of Earth tides in Thessaloniki

Symbol	Period T(min)	Signal/ noise	Amplitude (nms^{-2})	Origin
K1	1436	525.1	487.840	Lunar & Solar declination wave
O1	1549	379.7	352.816	Lunar principal wave
M2	745	1208.5	510.350	Lunar principal wave
S2	720	564.5	238.393	Solar principal wave

Table 4 displays the actual ocean corrected tidal parameters of O1 and M2 for Sofia, Instabul and Thessaloniki, and the corresponding values from the model of Wahr-Dehant-Zschau (Dehant 1987, Dehant and Zchau, 1989), expressing the dependency of the tidal parameters on the latitude. As it is shown from the table the amplitude factors of the principal O1 and M2 tidal constituents agree within their error of estimation with the model.

Table4. Ocean corrected parameters of O1 and M2 in 3 neighboring stations

	Sofia (latitude=42.71°)		Istanbul (latitude=41.07°)		Thessaloniki (latitude=40.63°)	
	Amplitude factor	Phase degree	Amplitude factor	Phase degree	Amplitude nm factor	Phase degree
O1	1.1493±0.0014	-.1590±.060	1.1564±0.0035	-.281±0.174	1.1536±0.003	-.201±0.151
Model	1.1540	-0.2	1.1542	-0.2	1.1543	-0.2
M2	1.1541±0.0005	-.207±0.026	1.1587±0.0011	-.039±0.026	1.1639±0.001	-.195±0.001
Model	1.1541	-0.2	1.1583	-0.2	1.1583	-0.2

For the latitude of 38° which is the mean latitude of the area under consideration, the extrapolated model amplitude factors for O1 and M2 are equal to 1.156 and 1.158 respectively. Consequently, the amplitudes of O1 and M2 might be changed to about 408 and 591 nms^{-2} respectively, which are very close to the amplitudes observed in the tidal station of Thessaloniki. However, this estimation does not take into account the actual elastic properties of the lithosphere in the area under consideration.

4. Method of Analysis

In order to check the possible correlation between Earth tides and earthquake occurrence we check the time of occurrence of each earthquake in relation to the sinusoidal variation of Earth tides and investigate the possible correlation of the time distribution of the earthquake events with Earth tides variation. Since the periods of the Earth tides component are very well known and quite accurately predictable in the local coordination system we assign a unique phase angle within the period of variation of a particular tidal component, for which the effect of earthquake triggering is under investigation, with the simple relation:

$$\phi_i = \left\{\left[\frac{(t_i - t_0)}{T_d}\right] - \mathrm{int}\left[\frac{(t_i - t_0)}{T_d}\right]\right\} \times 360 \qquad (1)$$

where ϕ_i = the phase angle of the time occurrence of the i earthquake in degrees

t_i = the time of occurrence of the i earthquake in Modified Julian Days (MJD),

t_o = the epoch we have chosen in MJD,

T_d = the period of the particular tidal component in Julian Days.

We choose as epoch t_o, i.e. as reference date, the time of the upper culmination in Thessaloniki of the new moon of January 7, 1989 which has MJD = 47533.8947453704. Thus the calculated phase angle for all the periods under study has 0 phase angle at the maximum of the corresponding tidal component (of course M2 and S2 has an upper culmination maximum every two cycles). As far as the monthly anomalistic moon concern the corresponding epoch t_o is January 14, 1989 which has MJD = 47541.28492.

We separate the whole period in 12 bins of 30° and stack every event according to its phase angle in the proper bin. Thus we construct a Cumulative Histogram of earthquake events for the tidal period under study.

A crucial point of this analysis is the use of a proper statistical test which will give us arguments to decide if such a result is correct or not i.e. will provide us a proper confidence level to our decision. To this purpose we use the well known Shuster's test (Shuster 1897, see also Tanaka et al. 2002; 2006 and Cadicheanu et al. 2007). In Shuster's test, each earthquake is represented by a unit length vector in the direction of the assigned phase angle α_i.The vectorial sum D is defined as:

$$D^2 = \left(\sum_{i=1}^{N}\cos\alpha_i\right)^2 + \left(\sum_{i=1}^{N}\sin\alpha_i\right)^2, \qquad (2)$$

where N is the number of earthquakes. When α_i is distributed randomly, the probability to be the length of a vectorial sum equal or larger than D is given by the equation:

$$p = \exp\left(-D^2/N\right) \qquad (3$$

Thus, p < 5% represents the significance level at which the null hypothesis that the earthquakes occurred randomly with respect to the tidal phase is rejected. This means that the smaller the p is the greater the confidence level of the results of the Cumulative Histograms is.

5. Results

Figures 3 to 8 display the Cumulative Histogram for all the 6291 earthquakes which occurred in the time interval from January 1st, 2013 to December 31st, 2013. These histograms correspond to the tidal periods of: Anomalistic Monthly period(i.e. time period between two successive passages of the moon from perigee which is $27^d.554551$) (Figure 3), Synodic Monthy period (i.e. period from new moon to new moon which is $29^d.530589$) (Figure 4), Diurnal luni-solar constituents K1 (Figure 5), Diurnal luni-solar constituent O1(Figure 6), Semi-diurnal solar constituents S2 (Figure 7), and Semi-diurnal lunar constituent (Figures 8), for the last year of the 50-year analyzed data, i.e. 2013. It is obvious that there is a perfect compliance of tidal and earthquake frequency distribution for Monthly Anomalistic and Synodic period, Diurnal luni-solar K1 and Semi-diurnal solar S2 periods and a smaller compliance for the Diurnal luni-solar O1 and Semidiurnal lunar period. This is shown in Table 5. This table displays the corresponding confidence levels for all six tidal components for 2013 together with the same quantities for a year of low tectonic activity, i.e. 1994 and the mean confidence levels for the

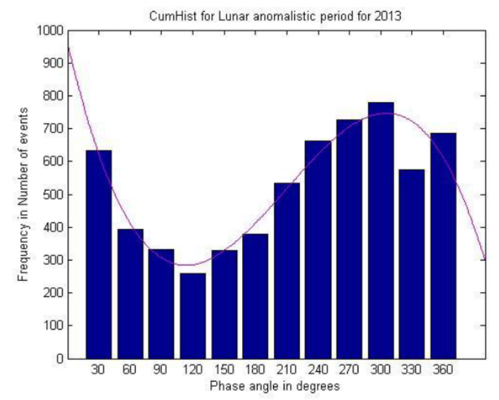

Figure 3. Cumulating Histogram for the Anomalistic Monthly period for 2013

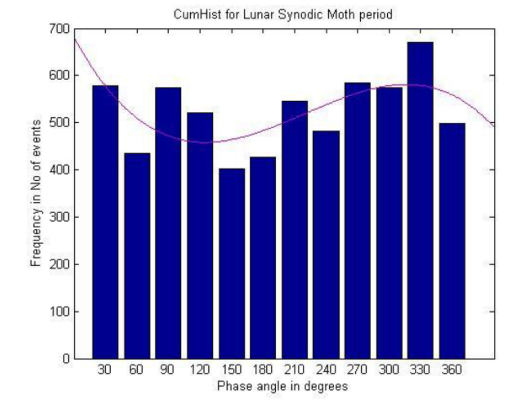

Figure 4. Cumulation Histogram for the Synodic Monthly period for 2013

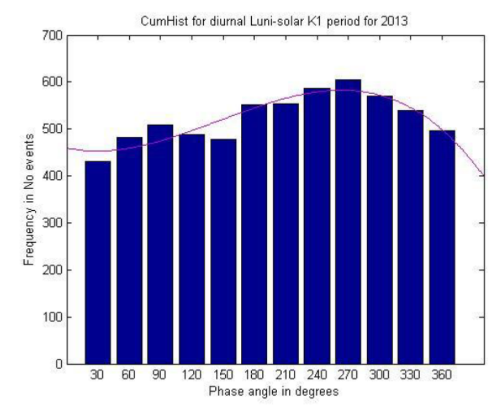

Figure 5. Cumulation Histogram for the Luni-Solar K1 period for 2013

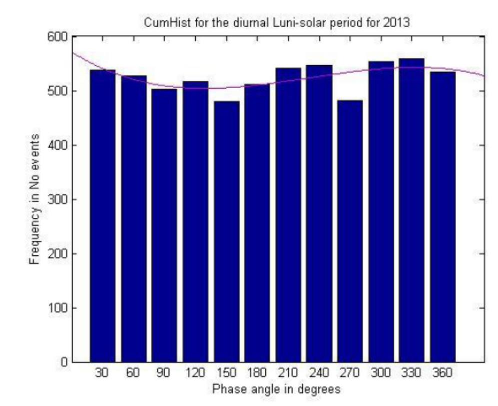

Figure 6. Cumulation Histogram for the Luni-Solar O1 period for 2013

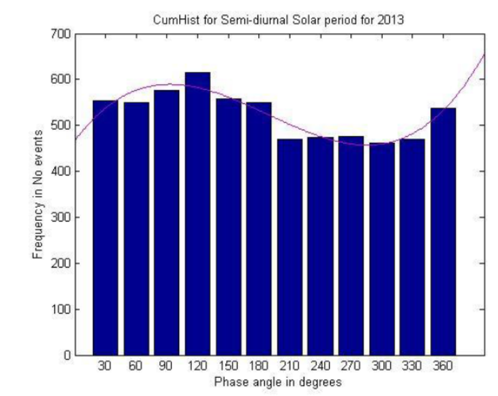

Figure 7. Cumulation Histogram for the semi diurnal Solar S2 period for 201

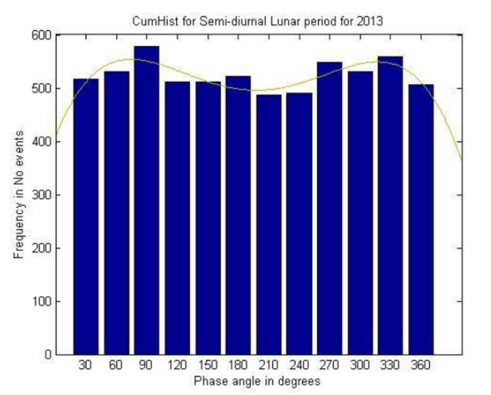

Figure 8. Cumulation Histogram for the semi diurnal Lunar M2 period for 2013

Table 5. The confidence level of earthquake-Earth tide correlation for all the earthquakes of Santorini area for 2013 in comparison with Mean and those of 1994

	MAnom.	MSynod	K1	O1	S2	M2
Mean	0.172	0.182	0.387	0.420	0.306	0.435
1994	0.971	0.481	0.470	0.791	0.816	0.812
2013	0.000	0.000	0.000	0.101	0.000	0.159

Table 5 indicates loudly that the confidence level of the Tidal-Earthquake frequency period compliance is very sensitive to the seismicity of the area. This is shown also in figures 9 to 14. These figures display the variation of the confidence level parameter in the time period 1964 to 2913 together with the earthquakes frequency for each year for all six periods. The high compliance for the monthly tidal components, despite their small intensity may indicate that they provide in general favourable conditions for the action of the much stronger tidal components K1 and M2. In this point we may refer to the fact that the monthly tidal barometric variations are quite sensitive to the seismic activity (Arabelos et al. 2008). Perhaps this peculiar coincidence merits further investigation.

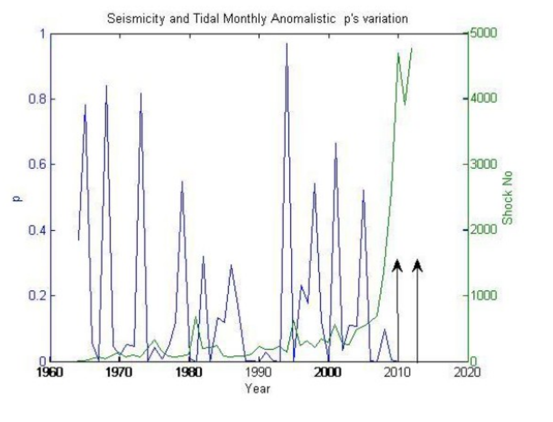

Figure 9. The confidence level parameter p between Seismicity and Tidal Anomalistic Monthly period. Arrows indicate the 5.2 M_L earthquakes at Aegion on 2010 and Fthiotida on 2013

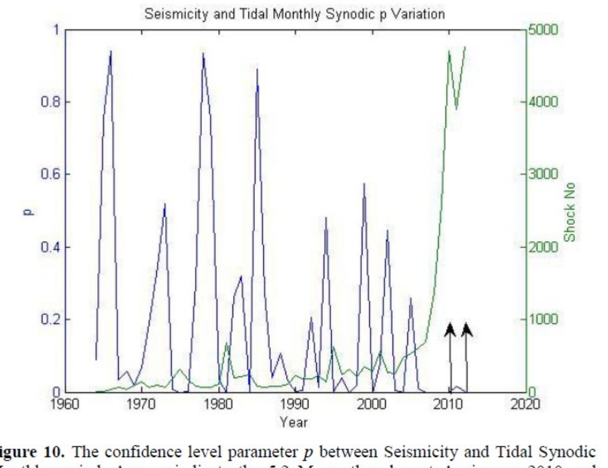

Figure 10. The confidence level parameter p between Seismicity and Tidal Synodic Monthly period. Arrows indicate the 5.2 M_L earthquakes at Aegion on 2010 and Fthiotida on 2013

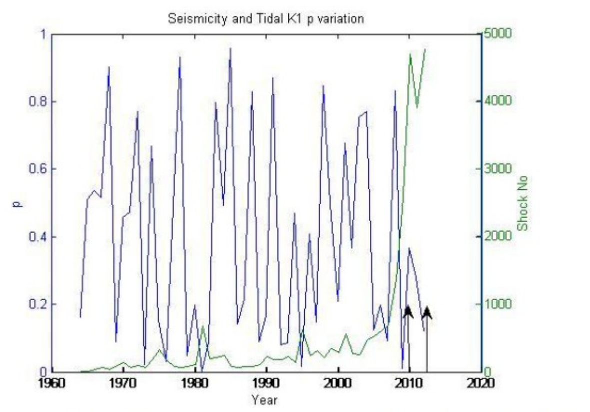

Figure 11. The confidence level parameter p between Seismicity and diurnal Tidal Luni-Solar K1 period. Arrows indicate the 5.2 M_L earthquakes at Aegion on 2010 and Fthiotida on 2013

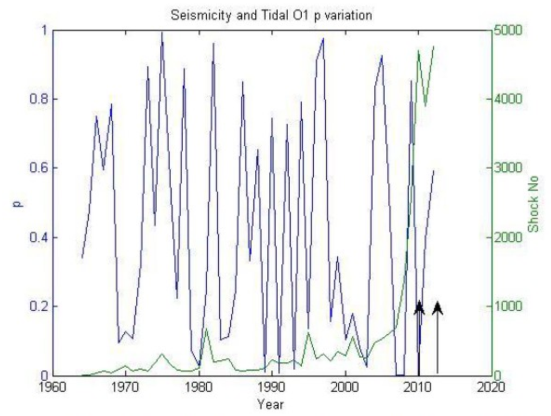

Figure 12. The confidence level parameter p between Seismicity and Tidal diurnal Luni-Solar O1 period. Arrows indicate the 5.2 M_L earthquakes at Aegion on 2010 and Fthiotida on 2013

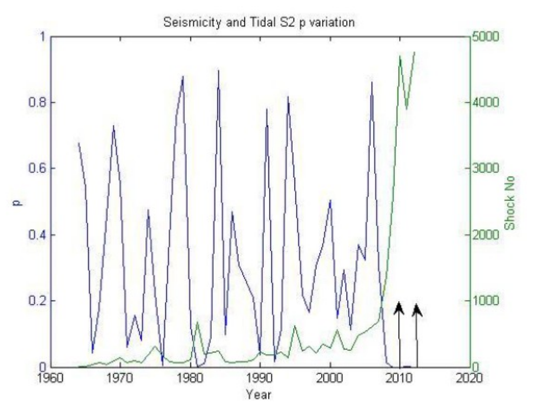

Figure 13. The confidence level parameter p between Seismicity and Tidal semi diurnal Solar S2 period. Arrows indicate the 5.2 M_L earthquakes at Aegion on 2010 and Fthiotida on 2013

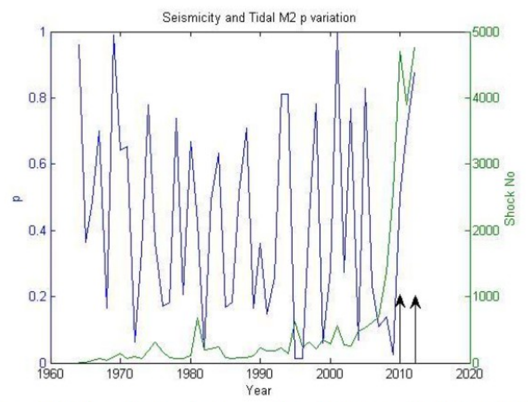

Figure 14. The confidence level parameter p between Seismicity and Tidal semi diurnal Lunar M2 period. Arrows indicate the 5.2 M_L earthquakes at Aegion on 2010 and Fthiotida on 2013

6. Conclusions

In this paper we investigate the tidal triggering evidence on the earthquakes of the area of Fthiotida in Greece. The result of our analysis using the HiCum method, indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly (Mf,Mm) variations. The same happens with the corresponding diurnal and semi-diurnal variations of the frequencies of earthquake occurrence with the diurnal (K1),(O1) and semi-diurnal solar (S2) and semidiurnal lunar (M2) tidal variations. The confidence level of the Tidal-Earthquake frequency period compliance is very sensitive to the seismicity of the area and we call it Tidal -Earthquake frequency compliance parameter. We suggest that this parameter may be used in earthquake risk evaluation.

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3 Method of analysis

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where f_i = the phase angle of the time occurrence of the i earthquake in degrees,
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, (2)

where N is the number of earthquakes. When α_i is distributed randomly, the probability to be the length of a vectorial sum equal or larger than D is given by the equation:

. (3)

Thus, $p < 5\%$ represents the significance level at which the null hypothesis that the earthquakes occurred randomly with respect to the tidal phase is rejected. This means that the smaller the p is the greater the confidence level of the results of the Cumulative Histograms is.

4. Results

Figures 3 to 14 display the Cumulative Histogram for all the 16,137 shallow earthquakes and the 1,482 deep earthquakes with local magnitudes > 2.5 which correspond to the tidal periods of: (1) diurnal luni-solar constituents K1 (Figures 3 and 4) and Semi-diurnal solar constituents S2 (Figures 5 and 6), (2) diurnal lunar constituent O1 (Figures 7 and 8) and semi-diurnal lunar constituent (Figures 9 and 10), (3) synodic month (i.e. period from new moon to new moon which is $29^d.530589$)