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A POSSIBLE LINK BETWEEN EARTH TIDES AND EARTHQUAKES

Tarek Kansowa[1] and Adrian Tatnall[2]

(1)National Research Institute of Astronomy and Geophysics, Space Research Laboratory, Helwan - Egypt

tsek@soton.ac.uk

(2)Southampton University, School of Engineering Sciences-United Kingdom, art4@soton.ac.uk

ABSTRACT

The ability of Earth tides to trigger earthquakes has been investigated statistically. Earthquakes occurring in the South of California and the Parkfield area with magnitude Mw ≥ 4.5 during the period 1973 to 2007 have been used. The earth tides vertical displacement has been calculated at the location and time of each earthquake. The relation between Earth tides and earthquake occurrences is measured statistically by applying Schuster's test. Each earthquake is assigned a phase angle between -180 and 180 degrees based on its occurrence time with respect to the local Earth tides. The value of p is used to determine the null hypothesis that earthquakes occur randomly with respect to the phase angle of the tidal variation. No significant correlation is observed between earthquake occurrence and Earth tides for the data set including all earthquakes. By classifying the data set according to the earthquake depth, a significant correlation has been found for shallower earthquakes (depth ≤ 6 km). A further analysis has explored the relationship between the earthquake occurrence and the Moon phase. The same data set has been used and Schuster's test indicates that there is a high relation between earthquake occurrence at shallow depths (depth ≤ 12 km) and the full Moon. The presence of aftershocks, however, does require a more detailed analysis to establish the true significance of this result as aftershocks can lead to clustering of earthquakes that could bias the results.

Key words: *Earth tides, earthquakes, Shuster's test, and tides prediction*

INTRODUCTION

1. Objective

In this paper the relationship between crustal motion and Earth tides is examined. The objective is to examine whether tidal forces can trigger earthquakes.

The area of interest is the South of California and the Parkfield area. These are defined as high earthquake risk areas. The Californian area is described as a large laboratory to study Earth displacements and earthquakes as the area is well covered by GPS stations and seismic instruments, and is also well covered by satellites such as Envisat, ERS2, which provide a lot of information about this area [Donnellan et al.,2002].

2. Evidence that tides can trigger earthquakes

It has been postulated for at least a century that earthquakes and Earth tides are linked. The stress associated with Earth tides can be up to 5x103Pa and in ocean basins water loading can build stresses up to nearly 5x104Pa (0.5 bars) [Cochran et al., 2004].

Whilst this stress is a small fraction of the stress released during an earthquake which is typically 5-50MPa for moderate and large earthquakes [Allmann and Shearer, 2009] there is evidence that the tidal effects could act as a trigger as the rate of change of the periodic stress change by the Earth tide is much larger than the rate of change of tectonic stress [Tanaka et al., 2006]. On the other hand, if additional stress is applied to a fault system that is near failure it is thought that this may initiate the rupture process that produces an earthquake [Emter,1997].

One of the earliest observations of possible relations was that for several days after an earthquake at Ito, Japan (1930), the number of earthquakes occurring per hour during low tide was higher than during high tide [Nasu et al, 1931]. Several recent papers have demonstrated a significant relation with certain types of earthquake. Tanaka et al, 2005, studied the relation between Earth tides and earthquakes that occurred before the 2004 Sumatra earthquake Mw= 9.0. The results showed a high relation for the ten years before the 2004 Sumatra earthquake especially around the initial rupture point of the main shock. They did not observe the same relation neither at other times nor over the larger region. They also observed that the peak earthquake occurrence occurred when the tidal shear stress was at its maximum. Their study suggests that if the tectonic plate stress is near critical condition, a small variation in the stress due to the Earth tide can trigger a large earthquake.

After the October 1983 Miyake-Jima volcanic eruption, for the next 14 days, the hourly number of earthquakes peaked at low tide and at high tide [Kasahara, 2002]. A further eruption on 8th July 2000 was followed by several earthquakes that showed a similar relation with ocean tides. Tolstoy, [2002,(9)] found an evidence that Earthquakes occur more frequently near low tides, especially the lowest spring tides, when the extensional stresses are a maximum in all directions. A possible explanation was the decrease in confining pressure when some of the weight of the ocean is removed at low tide. A different result was found by [Cochran et al., 2004] who found a better correlation of Earth tides with shallow earthquakes and when both Earth tides and ocean tides are taken into account large earthquakes were three times more likely to occur during high tides than low tides. A study of about 9350 earthquakes with magnitude 5.5 at least has investigated the relationship between earthquake occurrence and Earth tides [Tanaka, 2006]. The results show that a high correlation appears between reverse fault type earthquakes and Earth tides, and a significant correlation between large normal fault type earthquakes and Earth tides. There was less evidence that other types of faults have the same correlation with tides.

3. Earth Tides :

The Earth tide is the vertical tidal variation on the Earth surface. It consists of two terms; a direct term and an indirect term. The direct term is called body tide and is due to the tidal potential, the indirect term is called ocean load tide and occurs due to the ocean [Tanaka et al., 2006]. Earth tide also has another two components; a horizontal tilting and a horizontal displacement. Earth tides analysis is used to find out the parameters of the module which describe the Earth response to Earth tides taken into account the earth, station and sensor properties [Wenzel, 1997].

3.1 Tidal potential

At any point P on the Earth's surface the tidal acceleration $\vec{b}$ can be calculated as the summation of the gravitational acceleration $\vec{a}_p$ and the orbital acceleration $\vec{a}_0$. The tidal acceleration $\vec{b}$ can be formulated by using Newton's gravitational law and can be given as:

$$\vec{b} = \vec{a}_p - \vec{a}_0 = \frac{GM_b}{d^2} \cdot \frac{\vec{d}}{d} - \frac{GM_b}{s^2} \cdot \frac{\vec{s}}{s} \quad (1)$$

Where

G (the National gravitational constant) = 6.6672x10^{-11} m^3.

M_b = Mass of the celesitial body.

$\vec{d}$ = Topocentric distance vector.

$\vec{s}$ = Geocentric distance vector.

The tidal acceleration $\vec{b}$ can be calculated as the gradient of the tidal potential ν :

$$\vec{b} = \vec{grad}\ V = \frac{\partial V}{\partial \vec{r}} \quad (2)$$

Where

r = Radius vector

At geocentre $\vec{d}$ = 0, so as $\vec{r} = \vec{0}$, V= 0 and equation (2) can be written as:

$$V = GM_b \left(\frac{1}{d} - \frac{1}{s} - \frac{r.\cos\psi}{s^2} \right) \quad (3)$$

Where

Ψ = geocentric zenith angle

Using a series of Legendre polynomials $P_l(\cos\psi)$, equation (3) can be formulated as:

$$V = \frac{GM_b}{s} \cdot \sum_{l=2}^{\infty} \left(\frac{r}{s}\right)^l P_l(\cos\psi) \quad (4)$$

r/s is about 1.6*10^{-2} and 4*10^{-5} for the Moon, and the Sun respectively and so the series converges readily. In the most accurate catalogues l_{max} is equal to 6, 3, and 2 for The Moon, the Sun and other planets respectively [Wenzel, 1997]. About 98% of the tidal potential V comes from degree 2.

3.2 Earth Tides prediction

This analysis used the ETERNA 3.30 software package; a powerful tool which can be used for Earth tides data processing with high accuracy on all areas worldwide. It has been created by Wenzel 1996 and a lot of modifications and new models have been added to the software package. It enables recording, processing, analysis and prediction for all the tidal wave parameters for any place worldwide e.g. Earth tides gravity, displacement, strain, etc. to be predicted with high accuracy.

The tidal parameters for about 977 earth tides stations worldwide can be found on web address http://www.astro.oma.be/ICET/reg/Tidal_gravity_modeling.htm. The tidal parameters include the Oceanic tides.

The stations are grouped into 21 groups according to their geographical positions. The tidal parameters of the study area can be found in NORTH AMERICA group which contains about 93 stations. The web side provides fifteen tidal wave parameters (M0S0, SSA, MF, Q1, O1, P1, K1, J1, OO1, N2, M2, S2, K2, M3, and M4) for different types of earth tides prediction programs as Predict, MT80w and T-soft. A tidal parameters catalogue file has been created for the worldwide stations. The following information has been used; longitude, latitude, depth and gravity, amplitude and phase shift for the tidal wave parameters M0S0, SSA, MF, Q1, O1, P1, K1, J1, OO1, N2, M2, S2, K2, M3 and M4.

RESULTS

4.1 Earth Tides

On 22nd December 2003, an earthquake with magnitude M6.5 occurred in the central coast of the Californian area at latitude 35.706N and longitude 121.106W. This is known as the San Simeon earthquake. Nine months later another earthquake with magnitude M6 struck the same area again at latitude 35.815N and longitude 120.374W. This was located in the region around Parkfield, a region that lies on the San Andreas Fault and is characterised by regular earthquakes. Research to measure the Earth tidal vertical displacement during the occurrence of other earthquakes near the epicentres of both earthquakes during the period 1973 to 2007 has been done. Earthquakes with $M_W \geq 4.5$ have been chosen for this study in order to ensure that events larger than the background seismicity were selected. The research initially investigated an area of about 100km X 100km centred near the epicentre of both earthquakes in the Californian area. The number of earthquakes was too small to provide accurate results, so the area was enlarged until there were about 242 earthquakes of the required magnitude. The area assigned was from latitude 33.81N to latitude 37.81N and from longitude 122.37W to longitude 118.37W. The 242 earthquakes identified were used to investigate the relation between Earth tides vertical displacement and earthquakes occurrence in this area. The locations of all 242 earthquakes are shown in figure 1.

The earthquakes in the line running SE/NW all occur along the San Andreas Fault. Earthquakes to the NE are associated with the Long Valley Caldera; a depression in eastern California that is adjacent to Mammoth Mountain.

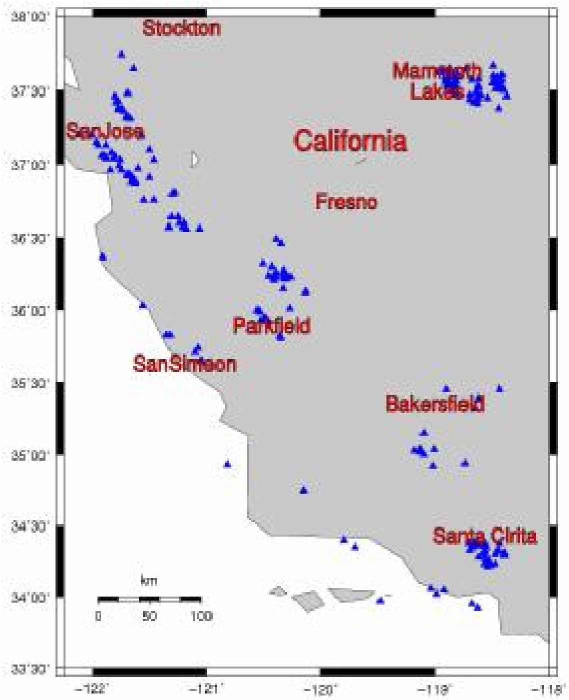


Fig. 1 : Earthquakes location with magnitude ≥ M4.5.

Statistical test:

The correlation between Earth tides and earthquake occurrences can be measured statistically by applying Schuster's test [Tanaka, 2002], [Heaton, 1982], and [Heaton, 1982]. If the time of the earthquake is plotted against the Earth tide a phase angle can be defined. This phase angle is between -180 to 180 as seen in figure 2.

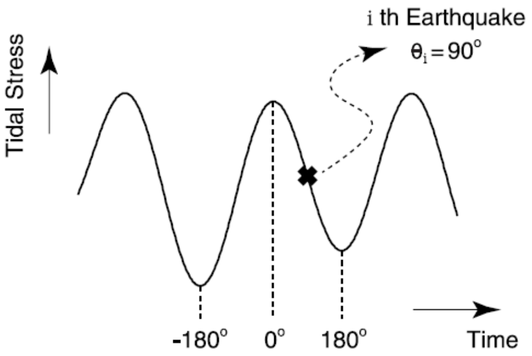


Fig. 2 : Tidal phase angle shift (Tanaka et al. 2002). Assign 0^{o} and $\pm 180^{o}$ to the maximum and the minimum of the tidal shear stress respectively just before or after each earthquake.. A linear scale with time has been used to calculate the tidal phase angle.

The Schuster's test is used to determine if the occurrence time of the earthquake has a correlation with the Earth tide variation. The Schuster's test can be given as:

$$D^2 = (\sum_{i=1}^{N} \cos\theta_i)^2 + (\sum_{i=1}^{N} \sin\theta_i)^2 \tag{5}$$

And

$$p = \exp(-\frac{D^2}{N}) \tag{6}$$

Where

N = Number of earthquake

θ = Phase angle shift

The value of p is used to determine the null hypothesis that the earthquakes occurs randomly with respect to the phase angle of the tidal variation. The value of p varies between 0 and 1, as p approaches 0 the null hypothesis that earthquakes occurs randomly tends to be small i.e. there is a positive correlation between the Earth tide phase and the occurrence of earthquakes. P is often required to be <0.05 to consider a correlation between Earth tides and earthquakes occurrence [Tanaka, 2002].

The results of p values can be seen in Table 1 where the p value has been calculated for different earthquake depths.

Table 1: P values for different earthquake depths.

Depth	Number of earthquakes	P value
All earthquakes	242	47.81 %
≤ 12 Km	199	32.59 %
≤ 10 Km	172	10.79 %
≤ 8 Km	117	6.46%
≤ 6 Km	80	4.73 %
≤ 5 Km	50	0.03 %

It can be seen that there is no correlation between the Earth tide vertical strain and earthquake occurrence when all the earthquakes are included. The p value reduces as the depths of the earthquakes included become shallower. For earthquakes occurring at a depth of 6 km or less, a significant correlation can be seen. The locations of the earthquakes occurring at depths of 6 km or less can be seen in figure 3.

Figure 4 shows the phase shift distribution and frequency distribution for different earthquake depths as in table 1.

The earthquakes are shown according to phase angle in bins of 45^{o} width. Following Tanaka (2002), the least square sinusoidal curve fitting has been applied to the frequency distributions. The equation of the least square sinusoidal curve fitting is:

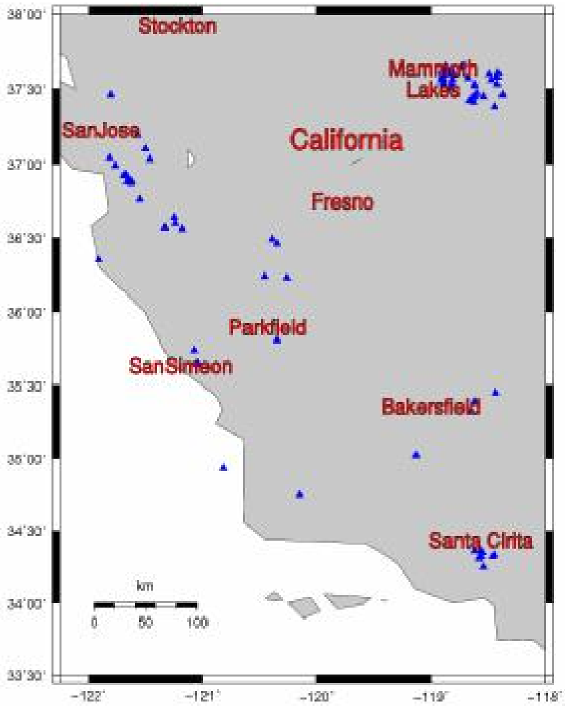


Fig. 3 : earthquakes locations with depth ≤ 6 Km.

$$P(\theta) = P_0 + P_1 \cos(\theta - \Phi) \qquad (7)$$

Where

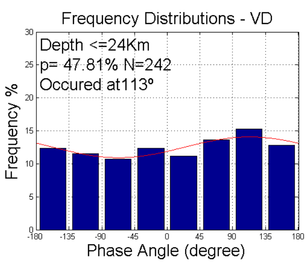
θ = Phase angle.

P_0 = Mean frequency.

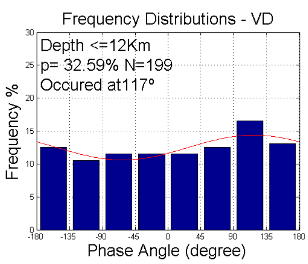
P_1 = Amplitude of the fitted curve.

Φ = Phase of the fitted curve.

(a) All Data

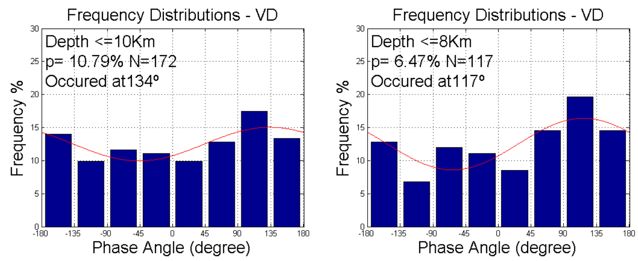


(b) Depth ≤ 12km



(c) Depth ≤ 10 km

(d) Depth ≤ 8Km



(e) Depth ≤ 6 km

(f) Depth ≤ 5Km

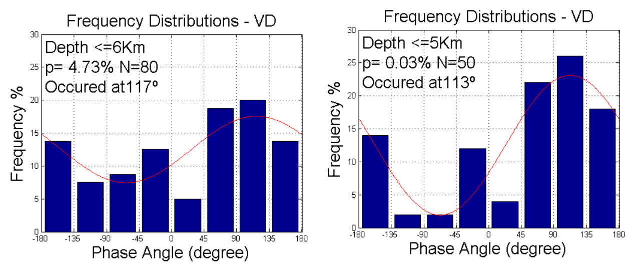


Fig. 4 : Phase and Frequency distributions.

The range of the earthquakes depths, the p value obtained by the Schuster's test, and the total number of earthquakes included in each data set is shown in the top left of each histogram. Also the tidal phase angle for each earthquake occurrence time for each set can be seen in the histogram.

Whilst the p value does decrease as earthquakes become shallower (Figure 4.a- 4.d), it is not until depths become 6 km or less where the correlation becomes significant. Figure 4.e shows the result of analysis using 80 earthquakes occurred at depth 6 Km or less. About 73 earthquakes with magnitude between 4.5 and 5.5 occurred within this set. A clear clustering of earthquakes at the phase window between 90° to 135° can be seen from the histogram, and the p value is significant (p= 4.73%). The results for earthquakes occurred at depth 5 Km and less (Figure 4.f) show a significant high correlation (p= 0.03%) which means, that there is a high correlation between earthquakes occurring at depth 5km or less with Earth tides. A total number of 50 earthquakes have been used to calculate the p values. The angle where these earthquakes tend to occur can be calculated by using equation 7. The phase angle at the peak of the occurrence frequency distribution is about 113^o. The gradient of the vertical displacement reaches its maximum at phase angle 90^o. The high correlation around this angle suggests a possible link between earthquakes and the rate of change of Earth tide vertical displacement.

4.2 Earthquakes and the Moon Phase

The amplitude of the attraction force of the Moon - Earth - Sun system varies through the lunar month as the relative position of the Sun and the Moon change. Figure 5 shows the Moon phase during the lunar month. The Earth tide is maximum during the new and full Moon and minimum during the first and the third quarter. Research work has been done to investigate the relation between earthquake occurrence and the Moon phase. Using the same data set, the lunar date of each earthquake has been calculated by using a calendar converter program online at web site http://www.fourmilab.ch/documents/calendar/. The Shuster's test has then been applied to find out if there is a correlation between earthquake occurrence and the Moon phase. The semidiurnal tidal range varies in a two-week or fortnightly cycle and so the time of the earthquake has been identified with respect to this cycle

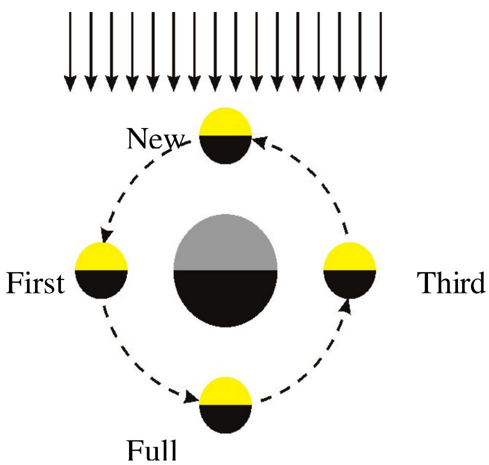
Before applying the Schuster's test, some modifications have to be done before it can be applied correctly. These can be summarized in the following steps:

1- The maximum difference between the high tide and low tide occurs during the new and the full Moon and the minimum difference between the high tide and low tide occurs during the first and third quarter.

2- The Moon phase angle is assigned at the occurrence time of each earthquake. It is measured from the maximum of the Earth tides that occurs closest to the time of the earthquake. The Moon phase angle can take a value between -180^o to $+ 180^o$ where $\pm180^o$ corresponds to the minimum Earth tide and 0^o corresponds to maximum Earth tides

3- The tidal phase angle for each earthquake (see Tanaka, 2002) can be calculated by a linearly dividing the time interval between the maximum and minimum of the tidal stress.

4- Apply the Schuster test to calculate the p value.



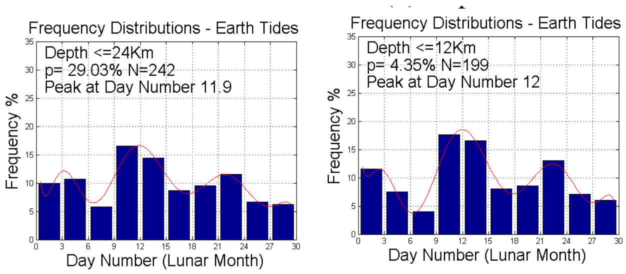
The results for the calculated p value are shown in table 2.

Table 2 : P values for lunar day number and earthquakes for different earthquake depths.

Depth	Number of earthquakes	P value
All earthquakes	242	29.03 %
≤ 12 Km	199	4.44%
≤ 10 Km	172	3.34 %
≤ 8 Km	117	15.58 %
≤ 6 Km	80	1.02 %
≤ 5 Km	50	43.73 %
>12 Km	43	2.71 %
>10 Km	70	5.2 %
> 8 Km	125	64.19 %
> 6 Km	162	21.08 %
> 5 Km	192	34.34 %

p values have been calculated for different earthquake depths. It can be seen that there is no correlation between the Moon phase and earthquakes occurrence when all earthquake are considered. Figure 6 shows the phase shift distribution and frequency distribution for the different earthquakes depths shown in table 2.

(a) Depth < 24 Km (b) Depth < 12 Km



(c) Depth ≤ 10 km (d) Depth ≤ 8Km

(e) Depth ≤ 6 km (f) Depth ≤ 5Km

(g) Depth ≤ 12 km (h) Depth ≤ 10Km

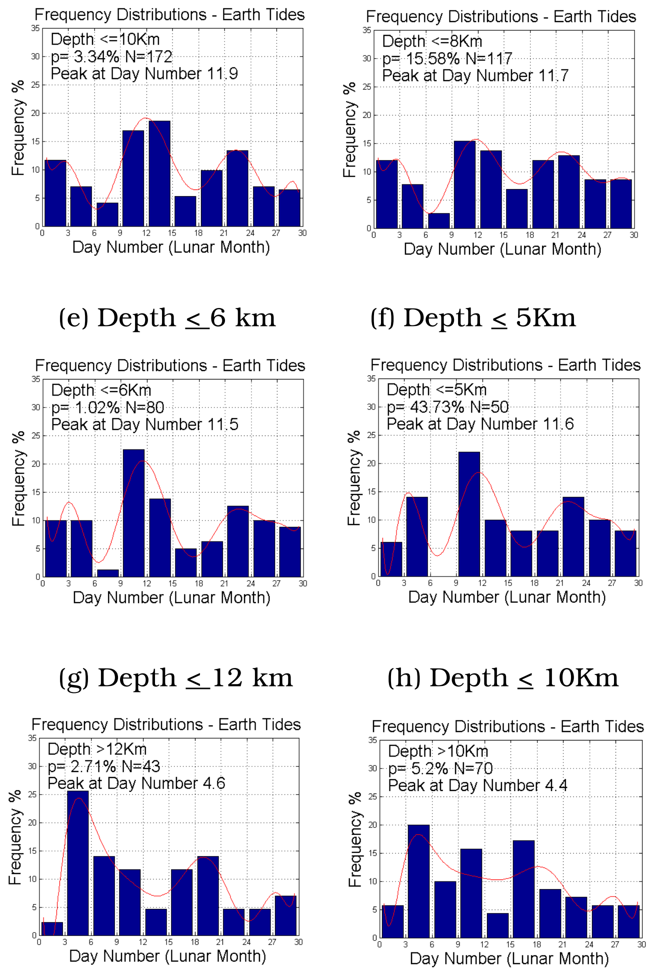


Fig. 6 : Frequency distributions.

Table 2 shows that when all earthquakes are included the p value is 29.03%. The p value reduces significantly when the earthquakes are classified into two sets; the first one for earthquakes at depths of 12 Km and less and the second set for earthquakes at depths greater than 12 Km. The number of earthquake is 199 for earthquakes occurring at depth 12 Km and less. The p value is equal to 4.44% and there is a trend of earthquakes to occur near day number 13 i.e. near the full

Moon. The result implies that there is a high correlation between earthquakes occurring at depth 12 Km and less and the occurrence of the full Moon. The analysis for earthquakes occurring at depth 10Km or less show that there is a good value of p (3.34%) and the earthquakes tend to occur at day number 12 while the p value for earthquakes occurs at depth 8 Km or less and 5 km or less are high. The p value is significantly small for earthquakes occurring at depth 6 Km or less. It should be noted, however, that the presence of aftershocks could be leading to a misleading conclusion. Aftershocks of an earthquake will occur in the same part of the lunar cycle as the original earthquake and with limited data will tend to bias the results. The table shows the p result for earthquakes occurring at depths greater than 12 Km. There are 43 earthquakes and the p value is 2.71%. The chart shows that the earthquakes trend to occur on day number 5 which is near to the first quarter of the Moon phase. A high correlation can be seen between earthquakes occurring at depths greater than 12 Km and the first quarter of the Moon phase. The other results for depths greater than 5,6,8 and 10Km, show no correlation between the earthquakes at these depths and the Moon phase.

CONCLUSIONS

The correlation between earthquake occurrence and Earth tides vertical displacement has been investigated for earthquakes with magnitude 4.5 or larger in the Californian and Parkfield areas. Schuster's test has been used to find out if the earthquakes tend to occur near particular phase angles or not. The results show that there is no significant correlation when all earthquakes are included. However there is a clear correlation between shallow earthquakes ($h \leq 6$ km) and vertical displacement. The same test has been carried out to investigate the relation between the earthquake occurrence and the Moon phase. There is a tendency for significant relations between the moon phase and earthquake occurring at depths of 12km or less.

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الملخص العربى

عــلاقـــة محتملــة بــين المـــد والجـــزر والـــزلازل

طــارق كانسوه[١]   أدريــان تاتنــال[٢]

المعهد القومى للبحوث الچيوفيزيقية والفلكية – حلوان – مصر ١

جامعة ثاوثمبتن، كلية العلوم الهندسية – المملكة المتحدة ٢

لقد تم إجراء دراسة إحصائية على إمكانية قوى المد والجزر على تحفيز حدوث الزلازل، ولهذه الدراسة تم إستخدام الزلازل التى حدثت بين عامى ١٩٧٣، ٢٠٠٧ جنوب كاليفورنيا ومنطقة باركفيلد ذات قدرة مساوية أو أكبر من ٤٫٥ ولقد تم حساب الإزاحة العمودية للمد والجزر فى وقت وموقع كل زلزال، ولدراسة العلاقة الإحصائية بين المد والجزر وحدوث الزلازل تم تطبيق إختبار شوست، وفيما يتعلق بالإزاحة العمودية للمد والجزر يتم تخصيص زاوية بين – ١٨٠ و ١٨٠ درجة تستند إلى وقت حدوث الزلزال، والقيمة التى تنتج عن إختبار شوستر لتحديد نسبة الزلازل التى تحدث عشوائياً مع الإزاحة العمودية للمد والجزر، وعند إستخدام مجموعة الزلازل بأكملها لوحظ عدم وجود إرتباط بين حدوثها وقوى المد والجزر، لكن عند تصنيف الزلازل إلى مجموعات وفقاً لعمقها لوحظ وجود إرتباط قوى بين حدوث الزلازل الضحلة (٦كم فأقل) والإزاحة العمودية للمد والجزر، وكذلك تمت دراسة لاستكشاف العلاقة بين حدوث الزلازل ومراحل القمر باستخدام نفس مجموعة الزلازل ونفس الاختبار الإحصائى، وأوضحت النتائج وجود علاقة إرتباط قوية بين حدوث الزلازل الضحلة (١٢كم فأقل) ومرحلة إكتمال القمر ونظراً لوجود توابع زلزالية فإن هذه النتيجة تحتاج إلى دراسة أكثر تفصيلاً لتحديد المغزى الحقيقى لها.

JOESE 5

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Tarek Kansowa[1] and Adrian Tatnall[2]

(1)National Research Institute of Astronomy and Geophysics Space Research Laboratory, Helwan - Egypt tsek@soton.ac.uk

(2)Southampton University, School of Engineering Sciences-United Kingdom, art4@soton.ac.uk

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