INDUCED SEISMICITY DUE TO THE OIL PRODUCTION IN TBILISI REGION, GEORGIA

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Introduction

30 km to the north-east from the Tbilisi hydrothermal field (THF) the oil field has been revealed. The intensive oil production in 80-s disturbs the regime of the central hydrothermal deposit and causes depletion and desalination of springs. Later on, after cessation of intensive extraction, the regime of hydrothermal field was recovered. These facts point to the significant change of pore pressure conditions during oil production process and triggered an idea to analyze the seismic activity in the period of oil production. As it is well known that the pore pressure change may provoke changes in the seismic activity (Gupta and Rastogi, 1976, Grasso and Sornette, 1998) the attempt is made to assess seismic effects induced by the oil production in the THF.

Geological and hydro-geological setting

The deposits of Lower-Eocene and Paleocene are widely presented in the Tbilisi region. They are composed of the granular sandstones, limestones and marls. The rocks are fractured intensively. This circumstance promotes formation of underground water basins in these deposits. The waters are of sulphite–hydrocarbonate–chloride–natrium-sulphite-natrium-potassium types. Total mineralization varies from 0.2 – 0.5 g/l to 4.4 g/l and increases from West to East.

The volcanic Middle Eocene deposits are the basic horizons of Trialeti and Teleti mountain ridge. They are represented by tuff sandstones, conglomerates, breccias and are characterized by intensive jointing; the joins mainly are open, which promotes free circulation of underground waters. Total thickness of Middle Eocene deposits is 500–800 m. Waters are of hydrocarbonate-sodium calcium-natrium, hydrocarbonate-chloride-sodium calcium-magnesium type. Total mineralization of waters fluctuates from 0.3 g/l to 1 g/l. Waters in these springs are of high temperature 40-50^{o} C.

Upper Eocene deposits are developed to the East of Tbilisi; they are composed mainly by clayey rocks with streaks of weak white sandstones. These rocks are water resistant. Total thickness of them reaches 1300 m.

It is evident that the main water-bearing complexes of thermal waters are Middle Eocene volcanic formations, located under Lower Eocene–Paleocene flysch deposits, opened by boreholes in Lisi and central section as well as by the productive oil boreholes in the Eastern part of tested area.

From the North, South and East the region is delineated by deep faults and one fault crosses the center of the city, following the valley of river Mtkvari.

Induced seismicity

We begin with considering the man-made effect of intensive oil production near THF that allow to judge about interconnections between oil field and Central thermal field. The effect of intensive oil pumping in the Samgori-Ninotsminda oil field on the water level (WL) in Botanical Garden borehole was the drastic change of pore pressure in the region, namely, in the water debit of the Botanical Garden well (1BG) located on the distance of 30 km from the production area.

According to (Grasso and Sornette, 1998) uploading of the earth's upper crust by hydrocarbon extraction of the order of magnitude of 10^{11} kg may trigger thrust events in a compressive setting 0.07 MPa. In Tbilisi region during 1970-1989 more than 5.10^{10} to kg of oil was produced so the level of extraction is close to critical. The stress change induced by hydrocarbon extraction is as a rule small, but according to data the deviatoric stress exceeding 0.01 MPa may trigger seismic activity. We calculated the order of stress change according to expression (Grasso and Sornette, 1998)

$$\mathbf{\Delta\sigma\ max=[1\text{-}2\nu/2\pi]pFmax(a/D)}$$

and obtained Δσ ≈0.06 Mpa, which is enough to induce seismic activity. In order to distinguish the seismohydraulic effect we plotted the seismic activity (SA) versus time in the time interval, covering periods before (1960-1970), during (1970-1989) and after termination (1990-2004) of oil production interval (Fig. 1). To exclude the effect of local seismic network changes during 1960-2004, only the catalog of the Tbilisi Seismic Observatory (TSO), where the registration conditions were not changed in this period has been used. In the analyzed catalog were included events occurred within circular area of radius 50 km around TSO. Three types of TSO catalog were analyzed: TSO1 included all events, recorded at the observatory, even smallest ones; TSO2 included only the events of magnitude $M \geq 2.5$; TSO3 included the events of magnitude $M < 2.5$ and TSO4 is the catalog of explosions, compiled by the Seismic Monitoring Centre of Georgia. According to the catalog TSO1 the SA increase in the hydrocarbon production period is evident.

At the same time there was a danger of contamination of data by some artifacts, for example by explosions which are common is the industrial area. Fig. 2 a, b shows that indeed the annual distribution of total explosion activity has a maximum in 1974-1988 years and the diurnal distribution – at 12 h G.M.T. At the same time the diurnal EQ distribution is quite different for different years of the period 1963-2005 (Fig. 3).

The distributions reveal very interesting details of local seismicity. Hystograms from 1960 till 1966 show almost random diurnal distribution of earthquakes (EQs). Beginning from 1966 some maximum of activity begins to appear at 12 hours by G.M.T. (8 hours by local time); in the interval 1973-1991 the maximum is very sharp and the majority of EQ occur in this time of day. From 1992 till the present day the unimodal distribution disappears and the distribution became random again. The dynamics of seismicity distribution can be explained by increase of industrial activity, in this case of the number of explosions from 1973 to 1991, because the explosions mostly were executed at 12 hours by G.M.T or at 8 h of local time (Fig. 3). Since 1991 due to political turmoil the industrial activity in Georgia including explosions was practically terminated (Fig.2).

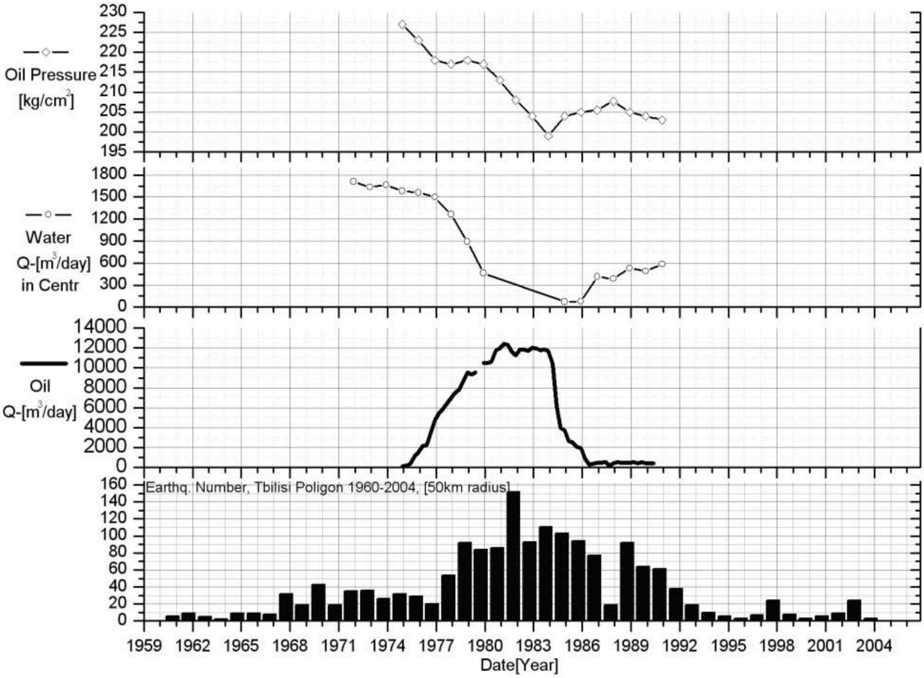


Fig.1. Underground fluids regime and seismic activity in Tbilisi hydrothermal field (THF); a) oil pressure (Samgori field), b) water debit in well 1BG (m^3/day), c) oil production (m^3/day), d) number of earthquakes per year 1960-2004 (according to catalogTSO1).

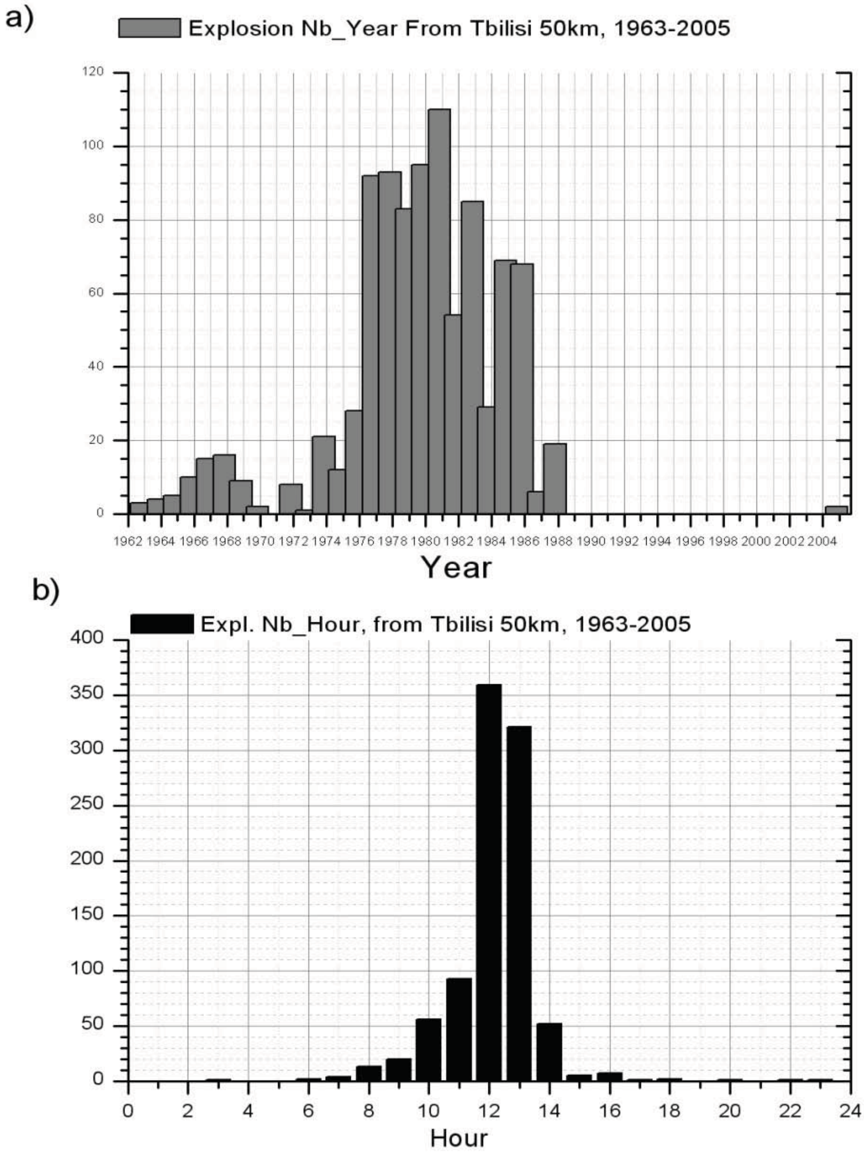
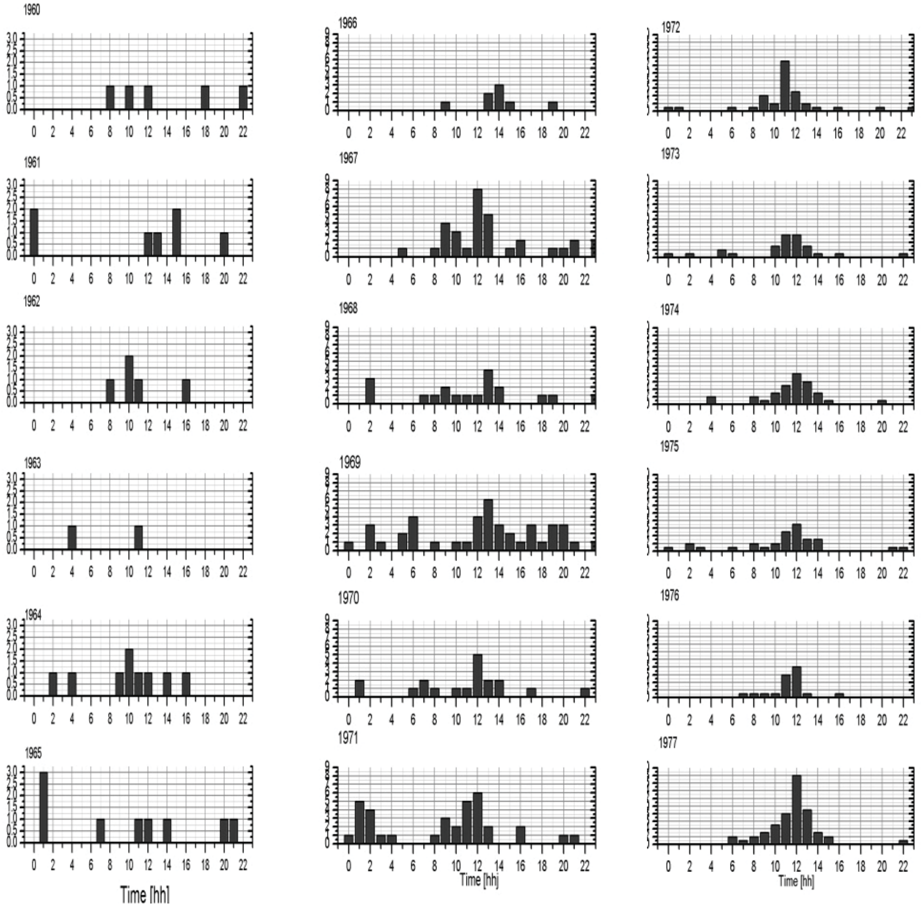


Fig. 2. a) Distribution of total number of explosions in Tbilisi region in 1960-2004; b) Diurnal distribution of total number of explosions in the same time interval.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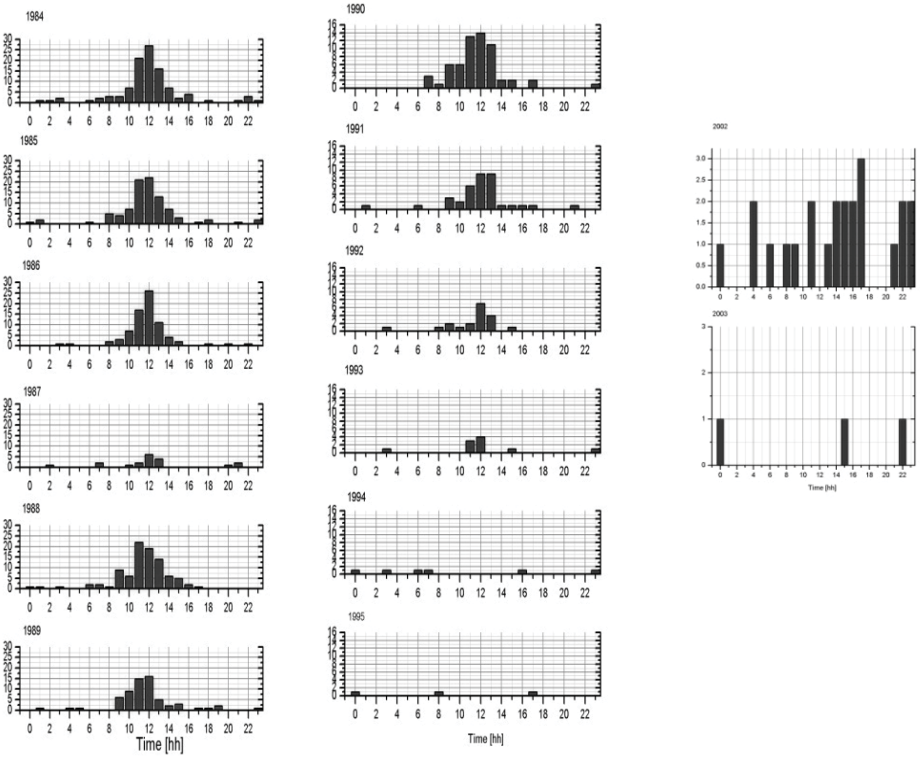

Fig. 3. Diurnal distribution of seismic activity in Tbilisi region for different years from 1960 to 2004. On the y-axis is given the number of earthquakes per hour.

As it could not be excluded that the maximum of SA was a consequence of explosion activity, from the catalog TSO1 were eliminated all events which occur around 12 h G.M.T, namely in the interval 10-14 hours (Fig. 4).

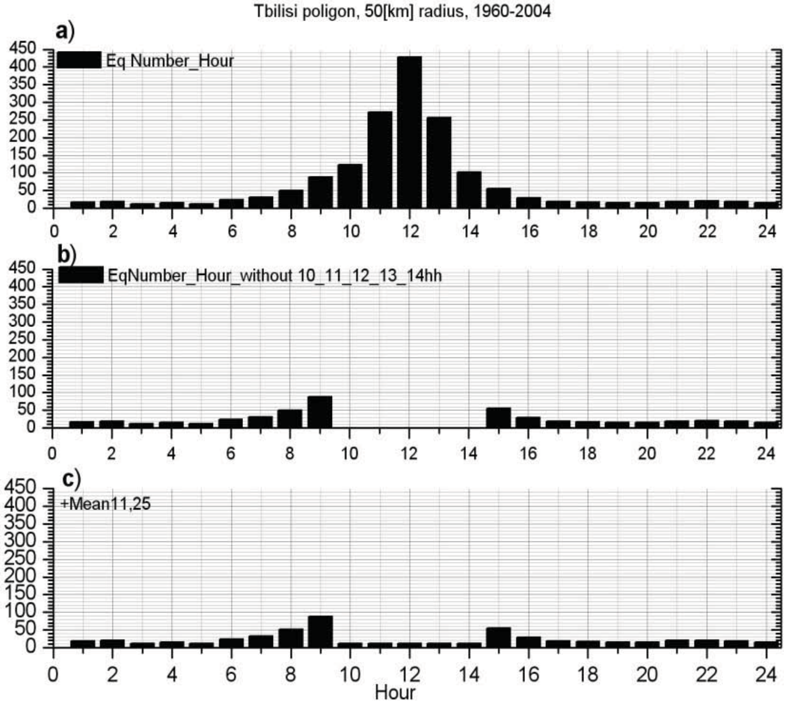

Fig.4. a) The diurnal distribution of SA from the catalog TSO1; b) The same without events which occur around 12 h G.M.T, namely without EQs occurred in 10, 11, 12 and 13 hours;

In order not to decrease the natural rate of seismic activity in the interval 12-14 h by total exclusion of seismic events, the mean annual number of EQ was added to the distribution in the above interval (Fig. 5).

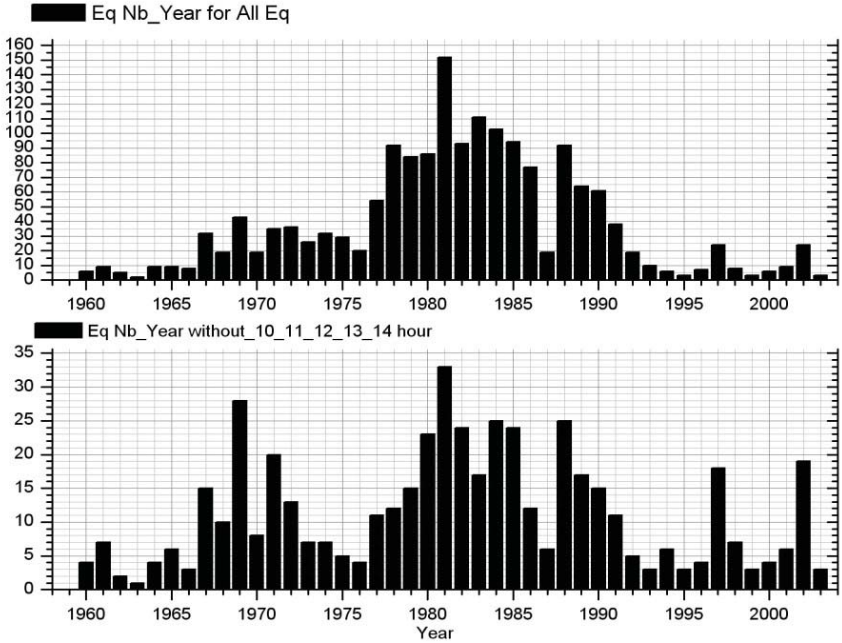

Fig.5. a) The annual EQs distribution , catalog TSO1; b) The same after exclusion of 4 hours interval around 12 h G.M.T. and addition instead of average (for 1960-2004) number of EQs per year.

It is evident that the increase of SA is present even after exclusion of possible explosion events. Besides the main maximum in 1974-1991 there are also three smaller maxima (Fig.5b). The SA rate increase around 1969, 1997 and 2002 are probably connected with the aftershock activity after relatively strong EQ of magnitude M ≥4 in mentioned years (Fig. 6).

It should be stressed that the increased SA around 12 h G.M.T is present even in the catalog TSO2 (Fig. 7), where only events of magnitude M≥2.5 are included; as explosions have not such amplitude this means that they can not affect the distribution.

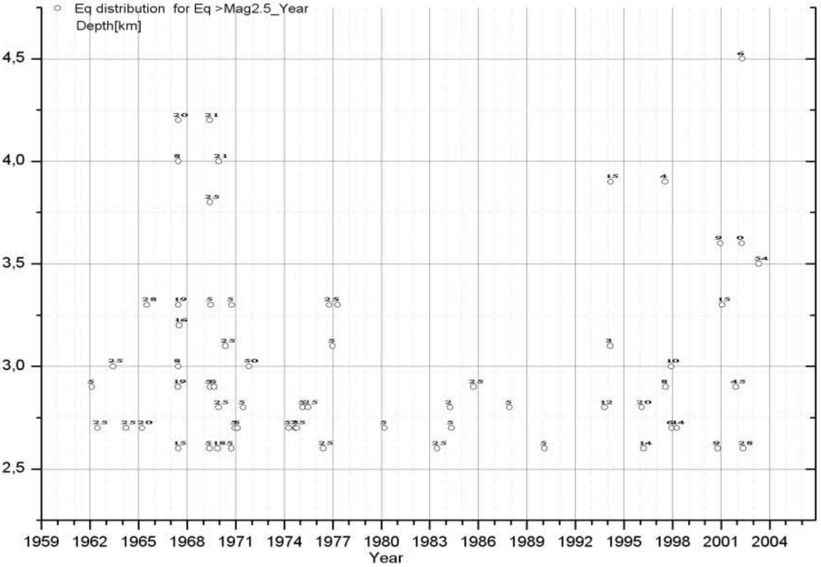

Fig. 6. Occurrence of earthquakes of M≥4 versus time in 1960-2004

All this evidence lead us to the conclusion that the time-dependence of SA in the period 1970-1989 in Tbilisi region reflects a complex process, which is affected by interaction of several factors. The main components of the process are: extraction of oil, change of pore pressure, industrial explosions, induced seismic events.

The most probable explanation of peculiarities in annual and diurnal distribution of EQ in connection with varying underground fluid regime in the region can be formulated in the following way: the intensive oil extraction in 1970-1989 changes the pore pressure distribution in the region and creates in the part of it Coulomb stresses which are favorable for fracture, i.e. a high strain sensitivity regime is created (Fig. 1). In the same period regular (around 12 h G.M.T) industrial explosions (Fig. 3, plots for 1970-1990) due to a high sensitivity of region to weak external impacts induce seismic activity of significant amplitude, namely events of M≥2.5, synchronized with the explosion regime, (Fig. 7) i.e. with a peak at 12 h G.M.T. The theory of synchronization as a universal concept as well as examples from various fields is given in (Pikovsky et al., 2003).

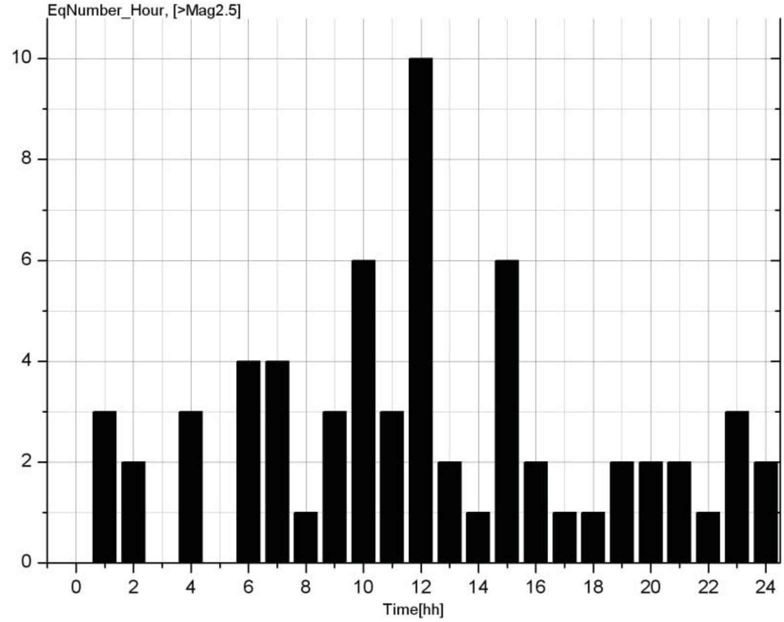

Fig. 7. Diurnal distribution of events of magnitude M≥2.5

Explosions, realized in the certain hour (hours) of the day can be considered as a weak quasiperiodic forcing superimposed on the much larger tectonic driving forces, which are also much slower than the forcing (the latter is a necessary condition for synchronization). The experimental laboratory studies confirm possibility of synchronization of acoustic/seismic activity under weak external forcing (Chelidze et al., 2003, 2005, 2006, 2007).

Of course, the synchronization of SA by explosion regime presumes the nonlinear interaction between tectonic processes and weak external impact, leading to forcing of SA by explosion.

One more interesting fact can be also marked: during 1970-1989 the number of strong seismic events decreases (Fig. 6) but the total number of events significantly increases. This can be interpreted as the result of quantification of SA due to synchronization phenomenon. The point is that synchronization controls not only the timing of seismic response – it can also regulate energy release: forcing means that synchronization limits the energy release associated with individual events as it promotes regular energy discharges so that very large strains can not accumulate in the medium (quantization effect). The suggested explanation has yet to be proved finally as the gap in the relatively strong SA can be connected with the natural peculiarities of regional tectonic process.

Conclusions

The analysis of fluid regime and seismic activity in the Tbilisi Hydrothermal Field (THF) before, during and after intensive hydrocarbon production in the period of 1971-1984 was carried out.

The fluid regime change in these years shows that the pore pressure in some part of the region decreased drastically causing extinction of thermal water spring.

Around the same period the seismic activity increased significantly. The effect is present even after exclusion of possible artifacts connected with industrial explosions and it can be seen in distribution of earthquakes of magnitude $M \geq 2.5$, which can not be identified as explosions.

The following hypothesis on the complexity of phenomenon is formulated: the oil production and pore pressure change in some parts of the region lead to changes in the Coulomb stress, which are favorable for triggering induced seismicity (there is nonlinearity in seismicity response to weak external impact). Due to high sensitivity of the region the induced seismic activity of significant amplitude is synchronized with the explosion regime, i.e. it reveals a peak at 12 h G.M.T even for earthquakes of magnitude $M \geq 2.5$.

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