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Evidence of seismicity induced by water level changes at the Mosul Dam reservoir and implications on the hydraulic diffusivity

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ABSTRACT - The relationship between Reservoir level and earthquake frequency at Mosul Dam's Reservoir shows an evident increases in seismicity following the yearly maxima in water level, with growths of epicentral area (hydraulic diffusivity), at about $9.3x10^4$ cm^2/sec. This value corresponds to permeability of about 8.4 x 10^{-11} cm^2. Seismicity concentration with time and space of their occurrences was obvious. A trend of 75.71 m/km of seismicity concentration towards the east and 9.676 m/km with depth was observed.

Keywords: Reservoir; seismicity; diffusivity; permeability.

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1. INTRODUCTION

Mosul Dam was constructed in 1986 at about 40 Km to the north of Mosul city, northern Iraq. It is an earth fill dam 100 m high and 3.6 km long and the maximum surface area of the reservoir is 419 km^2 with maximum capacity of 1.1^{10} m^3. During the monitoring period of this study (1986 and 1987) the reservoir was at its maximum storage.

The seismicity of Mosul reservoir was studied by Al-Saigh (2008), for the time interval April 1986 - end of December 1987 and it was found that the earthquake magnitudes range between 0.5 and 3.1 ML at rates of up to 3 events per week. Al-Saigh (2010) discussed the mechanism of the induced earthquakes at Mosul reservoir using the first motion of P-waves. It has been found that the mechanism of the earthquakes suggests right - lateral strike-slip faulting along N44°E striking plane, dipping 58° NW, in conformity with the regional tectonics of the area.

It is well known that seismicity patterns vary in both space and time. In space, the clustering of epicenters/hypocenters for small to large areas is often associated with the distribution of faults on which the seismic activity occurs (Hirata and Imoto, 1991; Wang and Lee, 1996). Regarding the clustering in time, it is seen as a local readjustment of the system following a perturbation of its stress field (Hirata, 1987).

The fact that clustering is observed both in space and in time should make us aware of the possibility of stress diffusion (pore pressure) phenomenon. Talwani and Acree (1985) suggested that the changes in pore pressure control the spatial existence and temporal pattern of reservoir induced seismicity (RIS). They observed a linear growth rate of epicentral area following impoundment of the lake. From these observations they suggested that the mechanism of transmission of pore pressure front to hypocentral locations was by a process of pore pressure diffusion. Their conclusions were based on the inference that the onset and migration of RIS is associated with such a pressure front. By monitoring the epicentral growth, and assuming it to be associated with the diffusion of pore pressure, they calculate the seismic hydraulic diffusivity parameter. Calculation of epicentral growth rates of induced seismicity gives an indication about the hydraulic nature of the reservoir (Bell and Nur, 1978; Talwani and Acree, 1985; Chen and Talwani, 2001).

2. GEOLOGICAL AND TECTONIC SETTING OF THE AREA

The rocks cropping out in the study area are dominated by the Fat'ha (middle Miocene) and the Injana (upper Miocene) formations, whereas, Euphrates/Jeribe (lower Miocene) and Pila-Spi (middle-upper Eocene) formations cover the rest of the area (Fig. 1). Fat'ha formation consists of a succession composed of limestone, marl, gypsum and anhydrite. The Injana formation, on the other hand is composed mostly of repetitions of sandstone, siltstone and shale, whereas Euphrates/Jeribe and Pila-Spi formations are composed mostly of limestone.

The dam site is bounded by two anticlines trending

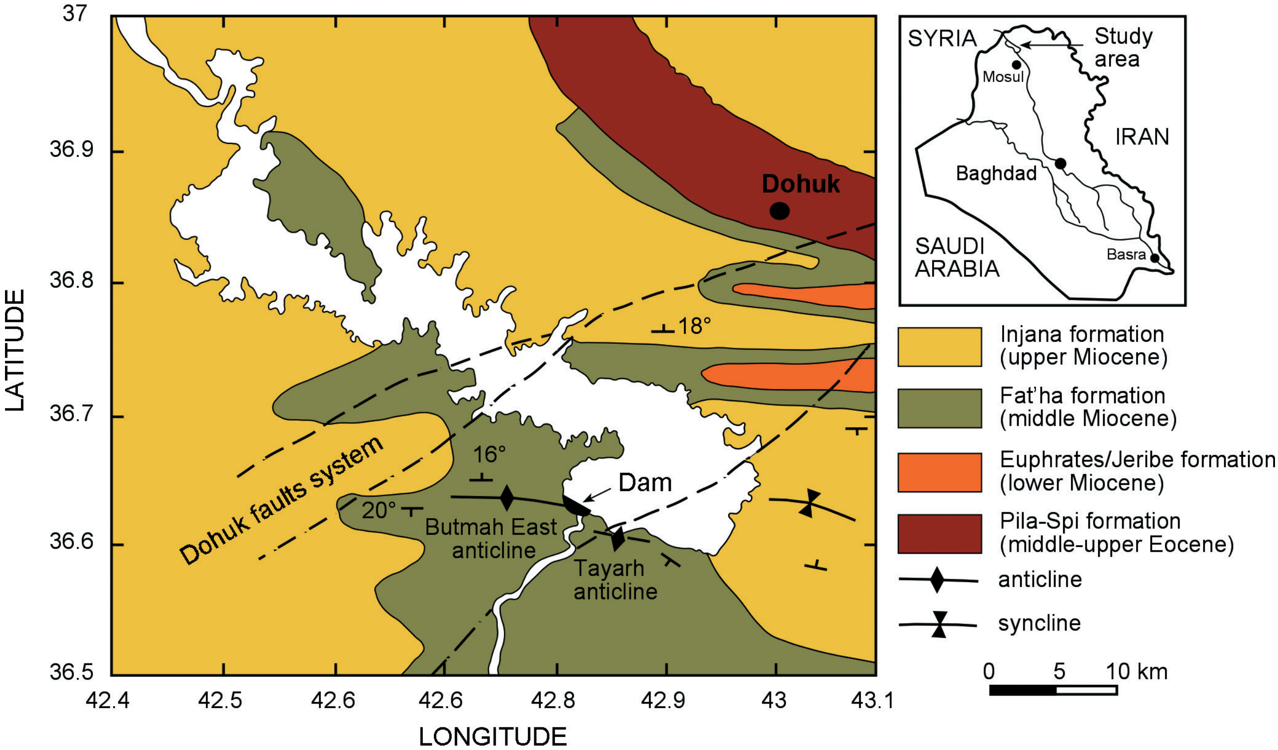

Fig.1 - Geological map of Mosul Dam Reservoir (Modified from the Geological, 1986 and Tectonic maps of Iraq, 1984).

E-W; namely Tayarh and Butmah East anticlines. Tayarh anticline lies on the eastern side of the Tigris River. It is a small anticline of about 4 km long and 0.5 km wide. Butmah East anticline, on the other hand, lies on the western side of the river. It is about 12 km long and 3.5 km wide (Tawfiq and Domas, 1977).

The south-southeastern boundary of the block is expressed on the surface by a complex strike-slip faults zone that are called the Sinjar-Dohouk-Kuchuk faults system. These faults run SW-NE and bound the southern border of Mosul reservoir, passing through its deeper parts (Fig. 1). The width (over a distance in S-N direction) of this faults zone is about 17 km, while no longitudinal extending faults have been identified. These faults are of particular potential source of seismicity, as indicated by Al-Saigh (2010) This is mainly due to the effect of pore pressure, water load and lubrication along these faults.

3. ANALYSIS OF SPATIAL DISTRIBUTION OF SEISMIC EVENTS

Figure 2 is a plan view showing the spatial distribution of earthquake epicenters in the area. Nearly all the epicenters were located within a radius of less than 25 km from the dam site. The majority of the epicenters were located in the lake region, in the area between the Sinjar-Dohuk faults system. A cluster of epicenters was observed in the eastern embankment of the lake and most of the hypocenters are located between the surface and 1.5 km depth. Figure 3 shows an evident trend of 75.71 m/km (taking that each 0.1 degree equal to 9.7 km) that the earthquakes tend to cluster along the longitude direction (towards the east).

Figure 4 shows the distribution of earthquake hypocenters with depth. Most of the hypocenters were located between the surface and 1.5 km depth. Very few were located between 1.5 km and 4.5 km depth. The figure shows a concentration of seismic event occurrence with depth of about 9.676 m/km in the longitude direction (towards the east), while there is no clear relation in the latitude direction.

4. ANALYSIS OF TEMPORAL DISTRIBUTION OF SEISMIC EVENTS

Figure 5 shows the monthly relationship between the reservoir's water level and a number of induced earthquakes. There are evident increases in seismicity following the yearly maxima in water level. The first highest water level was reached during the period of mid May to end of July 1986 corresponding with maximum seismic activity. The activity continued to the end of October long after the fall off the lake's level that occurred from August through December. The second highest water level was reached during May and June 1987. The maximum seismicity, however, was during the period September to December with a time lag of about two months. There was a two- month's delay period between the peak reservoir level and the peak seismic activity, which was most probably due to the pore pressure effect. A noticeable reduction of water level occurred during the period November 1986 and March 1987. Unfortunately, the network was out of order during this period to show

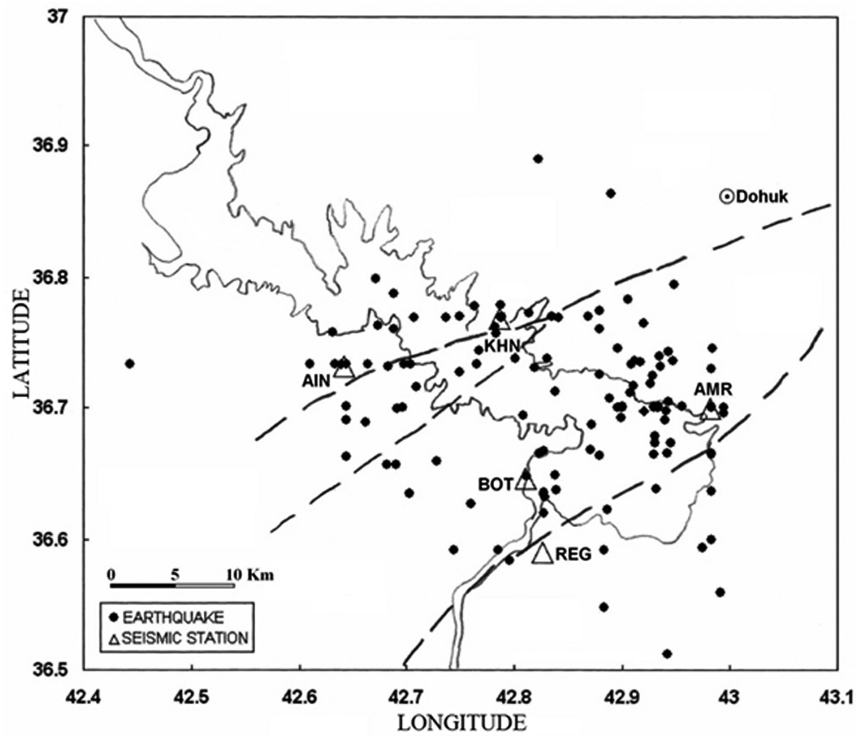

Fig. 2 - Seismicity map of Mosul reservoir for the period April 1986-December 1987.

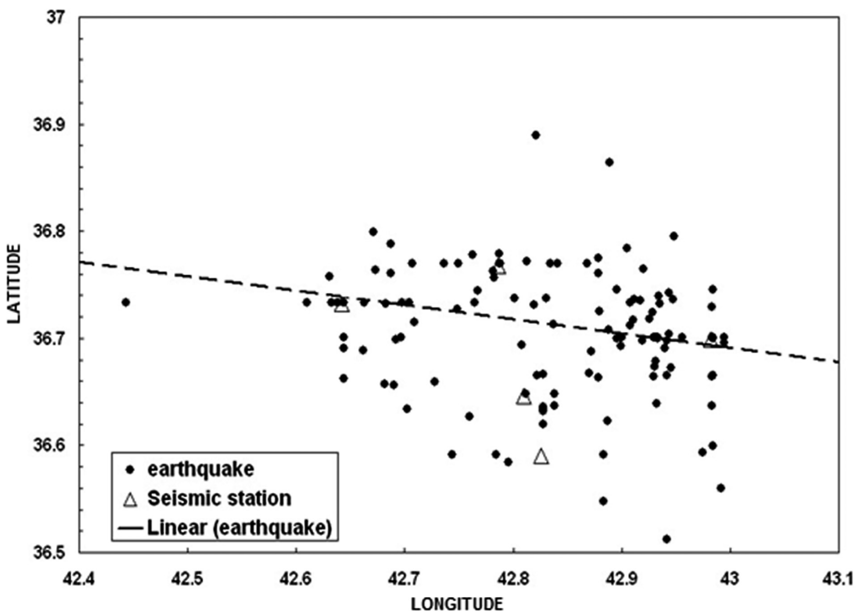

Fig. 3 - Seismicity map of Mosul reservoir showing a trend of seismic clustering along the longitude direction (towards the east).

the behavior of seismic activity during the period of low water level. The nearest national seismic station is located at Mosul city, which contains only strong motion seismograph that makes it not useful in recording small earthquakes occurring at Mosul dam.

Figure 6 shows the relationship between the location of epicenters in the x and y-directions (longitude and latitude) and the day of their occurrences, starting with the first earthquake occurrence in the 21st April 1986 corresponding with the day 111 on the x-axis. However, the figure shows a poor trend of seismicity concentration of about 8.97 m/day along the longitude direction. On the contrary there is no relation in latitude direction.

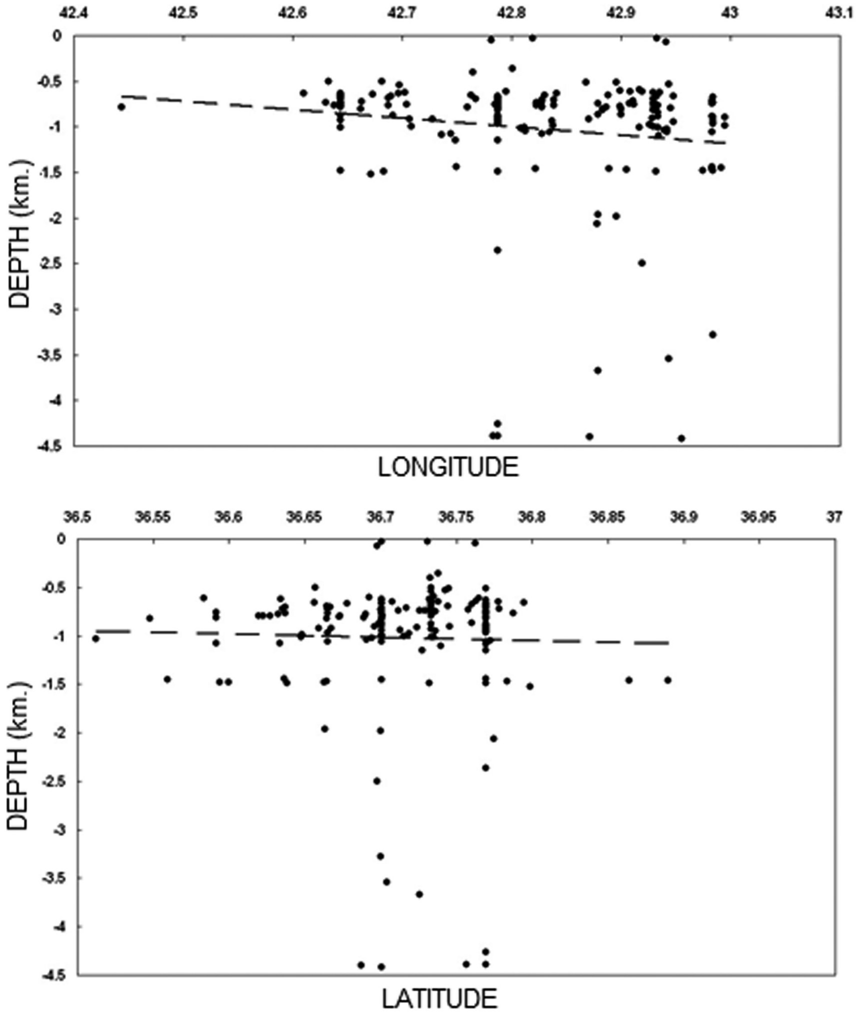

Fig. 4 - The distribution of earthquake hypocenters with depth showing a trend of increasing depth towards the east.

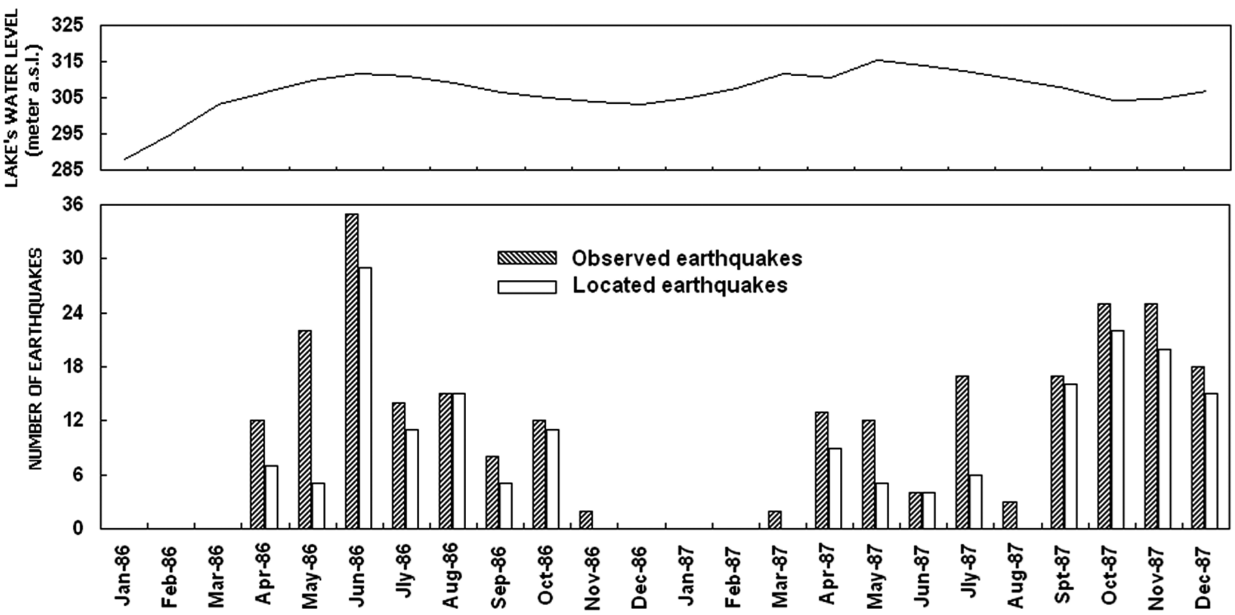

Fig. 5 - The relationship between water level in the lake and the number of earthquakes.

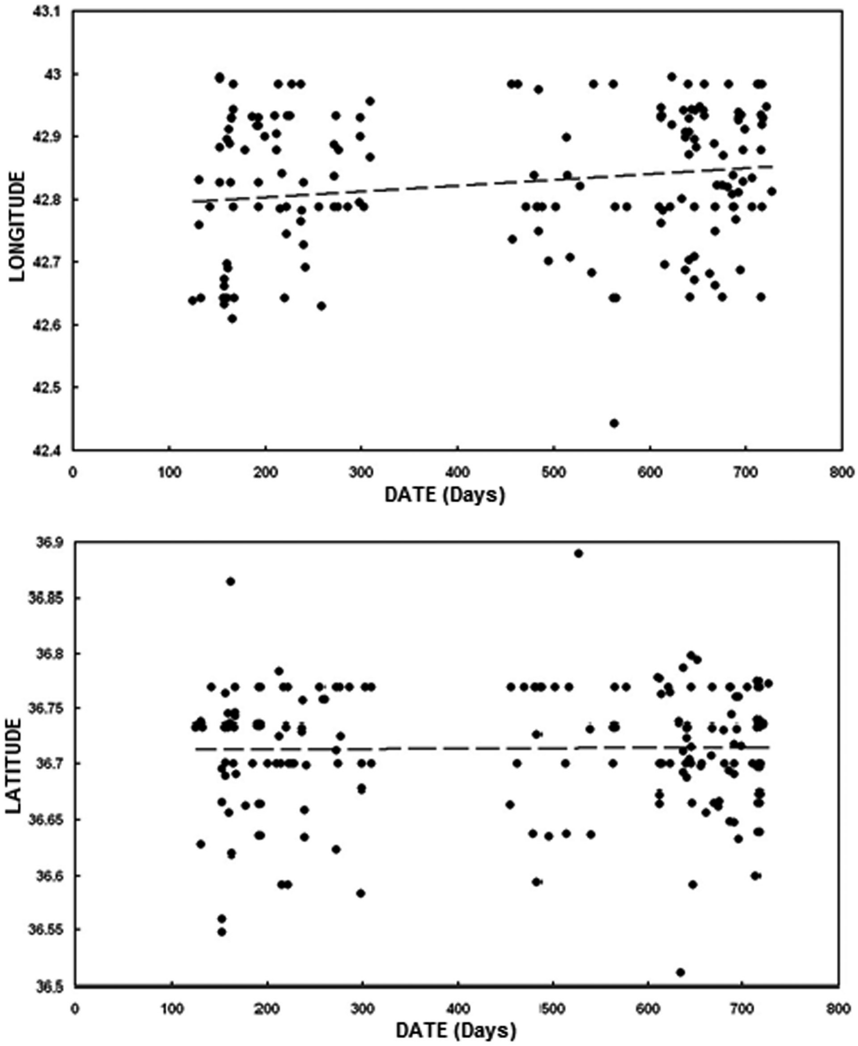

Fig. 6 - The relationship between the days of seismic event occurrences and their longitude and latitude locations.

5. GROWTH OF EPICENTRAL AREA AND SEISMIC HYDRAULIC DIFFUSIVITY

The space-time pattern of seismicity in Mosul reservoir was studied. The epicentral area of seismicity was considered for each three months of the monitoring period (starting from April 1986 to December 1987). The earthquake epicenters were plotted separately for each three months and encircled with a line representing the boundary of their occurrences, and then composite together. Very few events scattered far away from the concentration area were excluded (Fig. 7). In general the epicentral areas are taking an oval shapes extending roughly in an E-W direction, coinciding with the general trends of the faults in the area. However, the most characteristic feature of epicentral area is its relation with the reservoir level and number of observed events. The epicentral area related to October-December 1986 (area 3) is the smallest epicentral area. This is due to the recording was off from the 5th November 1986 to the end of March 1987. Therefore the hydraulic diffusivity between areas 3 and areas 2 and 4 was not considered (Tab. 1).

During 1986 it can be seen that there was an increase of epicentral area in the July-September time interval although there was drop in water level in the lake. This could represent a delay between maximum water level and the effect of pore pressure to induce earthquakes. This relation was not obvious during 1987 due to the lost of monitoring data for many days and weeks of this year.

The hydraulic diffusivity of Mosul reservoir was calculated by dividing the successive area difference in cm^2 on the time period (3 months) in seconds and it has been found that it ranged between $7.7x10^4$ to $1.1x10^5$ with an average value of $9.3x10^4$ cm^2/sec. This is within the range of hydraulic diffusivity obtained in other reservoirs in the world. Do Nascimento et al. (2004) found hydraulic diffusivity $3.4x10^3$ to 10^4 for Acu reservoir at Brazil. Talwani and Acree (1985) calculated the hydraulic diffusivity rate from over 30 cases and found that the epicentral growth ranges from $5x10^3$ to $6x10^5$ cm^2/sec with most values clustering around $5x10^4$ cm^2/sec.

These two values are associated with rocks having a permeability in the millidarcy range (0.1 to 10 md, or 10^{-12} to 10^{-10} cm^2). The larger hydraulic diffusivity values (~$X10^5$

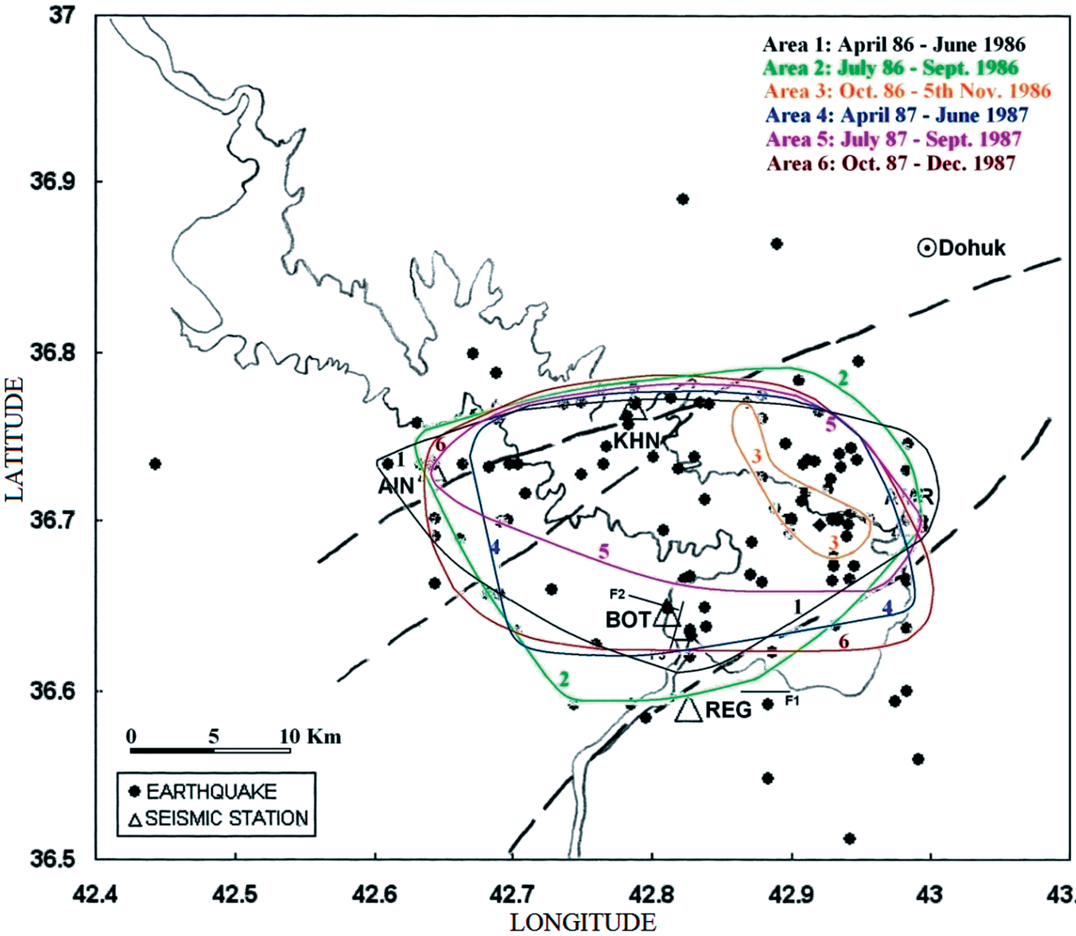

Fig. 7 - Envelope of the earthquake epicenters referred to different time-intervals in the Mosul Dam Reservoir area.

Area No.	Area km^2	Period in months	Period in second	Area difference km^2	Area difference cm^2	Hydraulic diffusivity cm^2/sec
1	434.4	April 86-June 86	7776000			
				71.4	7.14×10^{11}	9.2×10^4
2	505.8	July 86-Sept.86	7776000			
				476.0	4.76×10^{12}	6.1×10^5
3	29.8	Oct.86- Nov.86	7776000			
				351.0	3.51×10^{12}	4.5×10^5
4	380.8	April 87-June 87	7776000			
				59.5	5.95×10^{11}	7.7×10^4
5	321.3	July 87-Sept. 87	7776000			
				83.3	8.33×10^{11}	1.1×10^5
6	404.6	Oct. 87-Dec. 87	7776000			

Tab. 1

cm^2/sec) were obtained immediately after the main shocks and are probably associated with increased fracturing following the main shock, while Mukhopadhyay et al. (2010) pointed that the high diffusivity values indicate a highly inter-connected fractures.

The in situ permeability (k) of Mosul reservoir area was estimated to be ranging between $6.9\text{x}10^{-11}$ to $9.9\text{x}10^{-11}$ cm^2 with an average value of $8.4\text{x}10^{-11}$ cm^2 using the following simplified relation (Scholz et al., 1973; Brace, 1980).

$$k = \alpha S \ \mu \ \varnothing \ \beta f$$

where

αS = hydraulic diffusivity = $9.3\text{x}10^4$ cm^2/sec.

μ = viscosity of water = 10^{-2} poise = 10^{-8} bar sec.

$\varnothing$ = porosity of fractured rock = 10^{-2}–10^{-3}, say $3 \text{ x } 10^{-3}$ (Brace, 1980).

βf = effective compressibility of fluid = $3\text{x}10^{-5}$ /bar.

6. DISCUSSION

The temporal distribution of earthquakes at Mosul reservoir indicated an immediate increase of seismicity following the impounding of the reservoir in 1986 as a result of the instantaneous impact of the water load, while the delay of maximum seismicity in 1987 was due to the effect of pore pressure. Simpson et al. (1988) suggested that the temporal distribution of induced seismicity following the filling of large reservoir exhibits two types of response, instantaneous and delayed. They suggested that the seismicity that began immediately following the initial impoundment was due to the instantaneous elastic response, while the delayed seismicity was attributed to an increase in pore pressure. Talwani (1997) indicated that increasing of pore pressure away from the reservoir, resulting in delay between the filling and onset of seismicity. He indicated that the seismicity occurs in on the periphery of the reservoir and is usually associated with outward migration of epicentres along faults.

There was clustering in seismicity towards the east in a zone nearly parallel to a NE trending fault zones (Sinjar-Dohuk faults system). This zone is parallel to the strike of the fault plane inferred from the earthquake focal mechanism by Al-Saigh (2010) suggesting the effect of pore pressure diffusion along the faults system, consequently triggering earthquakes. Pandey (2006) indicated that the dominant mechanism of triggering earthquake activity in the Koyna-Warna region is through diffusion process which creates changes in pore-fluid pressure at hypocentral depths causing failure on preexisting critically stressed faults in the region.

Calculation of epicentral growth rates gives an indication about the hydraulic nature of the studied area. Knowing the fluid flow and permeability in a reservoir basin is of great importance for understanding the mechanism of induced earthquakes in the reservoir.

Mosul reservoir exhibits an average hydraulic diffusivity of $9.3\text{x}10^4$ cm/sec. This value is considered relatively high which may suggest the effect of the Dohouk Faults System on the initiation of the induced earthquakes. The concentration of induced earthquakes on the eastern embankment of the lake, especially along the faults system is due to the effect of pore pressure along these faults as advocated by Pandey (2006). The in situ permeability of Mosul reservoir was calculated as ranging between $6.9\text{x}10^{-11}$ and $9.9\text{x}10^{-11}$ cm^2. Bell and Nur (1978) suggested that lateral variations in permeability (e.g., along faults) can produce zones of increases pore pressure where net weakening can occur.

The widely distribution of Fat'ha formation in the Mosul reservoir area may have an effect on the distribution of seismicity. In general, the formation composed of different rocks types that have different permeability. Do Nascimento et al. (2004) postulated that variations in permeability leads to localized pathways of faster flow adjacent to areas of slow flow and hence the time at which the triggering pore pressure is reached at a given depth will vary.

7. CONCLUSIONS

Clustering of seismicity in both space and time characterizes induced seismicity were investigated in Mosul Dam reservoir. The spatial distribution of seismicity indicated clustering with time and depth of their occurrences. There was clustering in seismicity towards the east in a zone nearly parallel to a NE trending Sinjar-Dohuk faults system.

The temporal distribution of earthquakes indicated an immediate increase of seismicity following the impounding of the reservoir in 1986. The reservoir exhibits an average hydraulic diffusivity of $9.3\text{x}10^4$ cm/sec. The in situ permeability of the reservoir was calculated as ranging between $6.9\text{x}10^{-11}$ and $9.9\text{x}10^{-11}cm^2$.

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