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A Study on Shallow and Deep Focus Earthquakes and Relationship to the Water Level in the Western Side of the Aswan High Dam Lake, Egypt

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Abstract: On 07 November 2010, an earthquake of magnitude 4.6 struck to the south of Aswan City. The earthquake was followed by a few numbers of aftershocks that were recorded by a network of digital seismic stations operated by the National Research Institute of Astronomy and Geophysics, Egypt. These earthquakes are considered very important events, because they are located in a shallow zone along the Spillway fault, approximately 4.5 km to the north-west of the Aswan High Dam. The purpose of this study was to analyze and understand the relationship between the effect of the fluctuation of the water level on shallow and deep seismic activity at Aswan High Dam Lake in southern Egypt. During the period from 1981 to early 2011, the earthquake activity at Aswan Reservoir was separates into shallow and deep seismic zones. The Kalabsha fault is characterized by presence of shallow and deep seismic zones. The shallow earthquakes have focal depths less than 15 km, while the sources of deep earthquakes in this area are located at depths from 15 to 30 km.The shallow earthquakes along the Khor El Ramla, Kurkur and Spillway faults were better correlated with the water level changes in the Aswan High Dam Lake than the deep earthquakes. The study suggested that the induced seismicity in the Aswan High Dam Lake becomes active during a period when the water level is decreasing from the maximum to the minimum. The composite focal mechanism of two events in this study indicated a strike-slip faulting on nearly vertical fault planes. The strikes of the fault planes of the composite groups deviate in most cases from the average east-west and north-south strikes of the western desert set.

Key words: Aswan High Dam Lake · Shallow and deep earthquakes · Water level

INTRODUCTION

The terms shallow focus and deep focus (and a third term: intermediate focus) earthquakes relates to the depth below the earth's surface at which the earthquake occurs. An earthquake originates at a point known as the focus or hypocenter and most occur less than 70 km below the surface. Earthquakes occurring near the surface are known as shallow focus earthquakes. They are much more common than deep focus earthquakes and unfortunately they cause most damage on the surface because they are closer to the surface and therefore produce stronger shaking on the surface. Earthquakes induced by the water reservoir impoundment were observed in several places in the world. Reservoir increases stress by adding mass on the reservoir base and by increasing the pore pressure under and around the reservoir [1]. Aswan High Dam Lake in southern Egypt is the world's second largest reservoir to trigger induced seismicity. It produced an induced earthquake Ms 5.6 in Kalabsha area in 1981 and large numbers of earthquakes including several swarms are recorded. After the 1981 earthquake, the Aswan seismic network (13 stations) was installed by the cooperation between the National Research Institute of Astronomy and Geophysics (NRIAG) and High Dam Authority in collaboration with Scientists from the Lamont-Doherty Geophysical Observatory of Columbia University (Fig.1).

Induced seismicity refers to earthquakes that are caused by human activity. It occurs when this activity alters the stresses and strains in the Earth's crust. Most induced Seismicity is of an extremely low magnitude and in many cases, human activity is merely the trigger for an earthquake that would have occurred naturally in any case. There are a number of ways in which induced seismicity has been seen to occur and from these ways, the mass of water in a reservoir alters the pressure in the rock below, which can trigger earthquakes. Reservoir-induced seismic events can be relatively large compared to other forms of induced seismicity.

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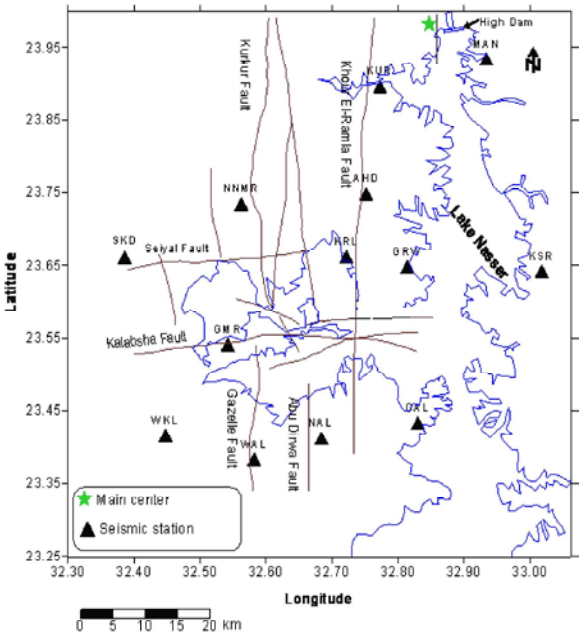

Fig. 1: Aswan Seismic Network Stations and the main faults in the studied area

There are a few cases of smaller magnitude earthquakes being triggered in the vicinity of artificial water reservoirs. It also be noted that a substantial number of these sites are located in the stable continental regions [2]. Noteworthy among these are Koyna (India), Kariba (Zambia and Zimbabwe border), Hsinfengkiang (China), Aswan (Egypt), etc.

After the occurrence of November 14, 1981 earthquake, with magnitude 5.6 on Richter scale at Kalabsha area, southwest of the Aswan High Dam, many researches on characteristics of the seismic activity in surrounding areas of Aswan High Dam Lake have already been carried out and published [3-9] and others. Occurrence of this sequence of earthquakes raised many questions about the possibility of future local earthquake activity in particular the proximity of this activity to Aswan reservoir. Lack of reported earthquake activity prior to the filling of the reservoir suggested the possible influence of the reservoir as a cause of the seismic activity in the area.

Tectonic Setting and Seismoactive Faults of the Studied Area: The geology of the western side from the Aswan High Dam Lake is controlled primary by regional basement rock uplift and regional faulting. The River Nile divides Aswan area into Eastern and Western areas. The area West of Aswan is characterized by great number of faults and the largest faults are Kalabsha and Seiyal faults. According to Issawi [10] the structural pattern of the investigated area is governed mainly by faulting. Folds are of secondary importance and they are either associated with fault lines or with uplifted basement rocks. Faulting that cross the area are classified into several systems depending on their trend. The most important of these is the E-W and N-S system. Seven faults were identified as active faults. These faults include Geble El-Barqa, Kurkur, Khor El-Ramla, Gezelle and Abu Dirwa fault (Fig.1). The N-S trending Spillway fault considered the source of the Nov., 2010 earthquake. It splits to the North into several subparallel faults and it is located approximately one kilometer to the West of Aswan High Dam. It is a vertical and inactive fault and the total length of this fault is 4.0 km [11].

Shallow and Deep Seismic Activities of the Studied Area: Several studies were carried out for the determination of sources and causes of earthquakes in this area [12, 13]. Some authors restricted the occurrence of these events to the artificial lake of Aswan reservoir, while others related this activity to tectonic deformations.

W.C.C. [11] concluded from studying the historical and recent seismic activities that a low level of seismic activity characterizes the area. The majority of local earthquakes recorded by a temporary network from Dec. 13, 1981 to July 6, 1982 were concentrated along the Kalabsha fault. Abou Elenean [14] has studied the spatial distribution of seismic activities at this area in different directions parallel and perpendicular to the fault trends. He concluded that, the seismic activity beneath Gebel Marawa (Western Kalabsha) took place at larger depth range, from 15 to 25 km and becomes shallower towards east (< 10 km). The activity along the other faults and trends indicates that most of the activity took place at shallower depth, from zero to ten km.

Awad and Mizoue [15], Hassoup [16], Mekkawi *et al*., [17] have shown that the shallow and deep seismic zones are characterized by low and high seismic velocity anomalies, respectively. Seismicity of deep seismic zone exhibits a tight cluster and is characterized by a permanent low level activity since 1984. In contrast, the shallow earthquakes occurred more frequently and were distributed along different fault segments; e. g. Kalabsha, Sayail and Kurkur faults.

More than 10953 events with local magnitude ranging from 1 to less than 5 at the period from 1982 to the end of 2010 were observed and recorded by the Aswan seismic network and most of these events are concentrated along the Kalabsha fault zone and Rawraw trend (Fig. 2).

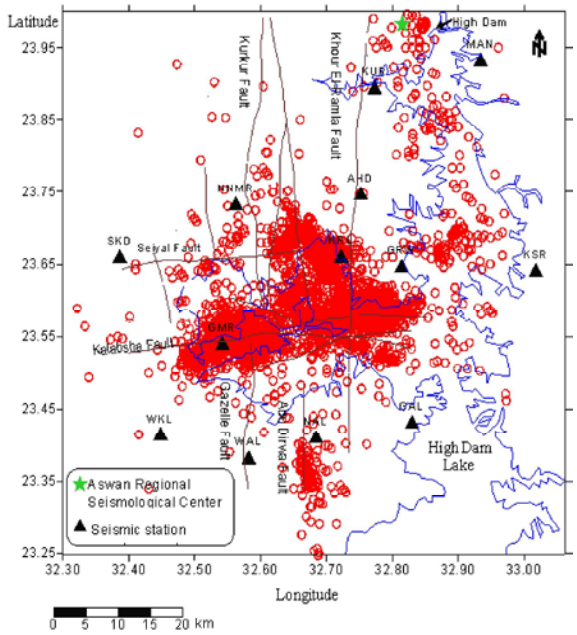

Fig. 2: Seismic activity in and around High Dam Lake from July, 1982 to Dec., 2010

Seismicity at Aswan region is continuing at a low level till now and mainly occurred near the epicenter of the main shock of 1981 along the Kalabsha fault near Gebel Marawa. The shallow seismic activity was believed to be triggered by the Aswan High Dam Lake. The earthquakes may be partitioned into two major groups in terms of depth characteristics. Shallow earthquakes of depths equal to about 15 km as shown in figure 3. The second group for deep quakes located at depths of about 30 km. The Seismicity map of the western side from Aswan High Dam Lake (Figure 2) showed that, the seismicity is concentrated in five main cluster zones. The first active zone extends 14 km along the Kalabsha fault from western foot of Gebel Marawa. The hypocenters are concentrated at two depth intervals: from 15 to 30 km and from 0.5 to 15 km. The second zone is less active and is located close to the old stream of the River Nile toward the north. In this zone, the activity is concentrated at depths between 2 and 7 km. The third zone includes all the shallow activity between 0.0 to 10.0 km and it is located north east of Gebel Marawa and on the Khor El-Ramla fault. The fourth zone is characterized by low and shallow Seismicity. It may be associated with a major North-South fault which extends from Kalabsha to Idfu and the latter zone is located south of Kalabsha fault and it associated with the Abu Derwa fault, this is the only active zone located away from the reservoir in an area that has not been covered with the reservoir water.

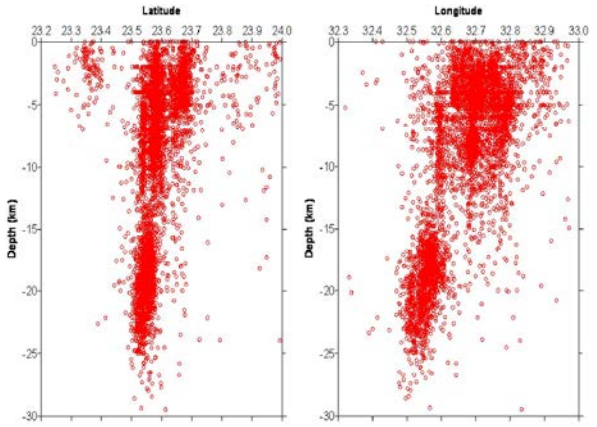

Fig. 3: Vertical cross sections show the depth distribution of the earthquakes

This study observed a number of seismic swarms occurred in Kalabsha area. The first swarm occurred on June, 1987 with largest magnitude of MD= 3.7. Its hypocenters were located within the shallow depth's interval (i.e. 2 to 10 km from the ground surface). The second swarm sequence took place to the north of the June 1987 sequence during the period from August to December 2004 with larger magnitude of MD= 4.1, it is a shallow seismic sequence too. The decreasing rate of water level in the Aswan High Dam Lake through 2004 was low in the first three months and reached its maximum in July, 6 cm/day. The loading rate was very high through August and September. It reached 17 cm/day on August 29. In this year, many earthquakes were monitored with different magnitude in both the loading and unloading seasons.

The third swarm occurred recently in the eastern part of Kalabsha fault on April 12-14, 2007 having a peak magnitude of 4.2, accompanied the decreasing rate 2 cm/day and the water level in this day (12 of April) was 175.18 meters. Aswan seismic network recorded about 262 shocks in this period, eleven of them had a magnitude greater than or equal to 3.5. Finally it should be noted that the relation between water level in Aswan High Dam Lake and induced Seismicity through the period from 1982 to 2010 seem to occur in intermediate or low stress situations with no clear indications of such activity found.

The Relation Between Fluctuation of the Water Level and Earthquake Activity: The change in level of any lake is controlled by the difference between the sources of inflow and outflow, compared to the total volume of the lake. One of the factors that have been observed to have a significant effect on the rate of Seismicity at reservoirs is

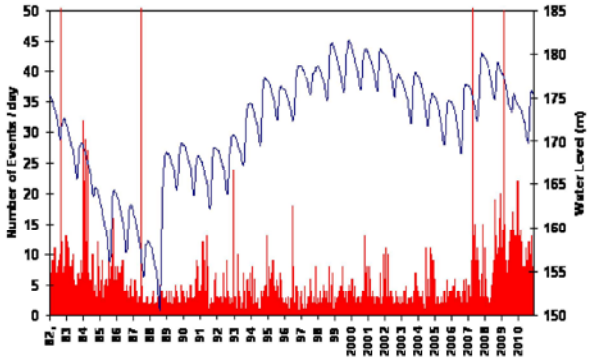

Fig. 4: Water level in the Aswan High Dam Lake and the number of earthquakes per day during the period from 1982 to 2010

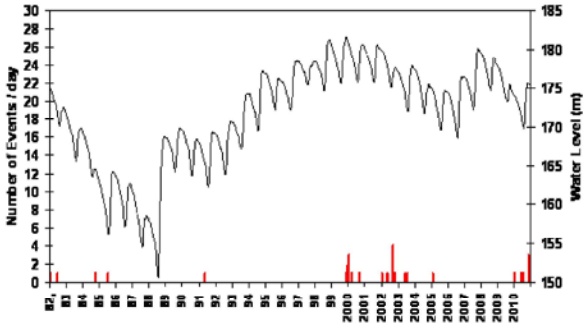

Fig. 5: Relation between water level in Aswan Lake and shallow earthquakes in and around Spillway fault during the period from 1982 to 2010

the way in which the water level changes in the reservoir [18, 19]. Variations in filling rate are strongly influenced by the type of utilization of the reservoir, local climatic conditions and topography. In addition to the importance of water level changes the steady-state utilization of the reservoir, the pattern of reservoir filling from first impoundment to maximum capacity is important in terms of triggered Seismicity. Depending on reservoir size, climate, topography and utilization and construction practices, some reservoir fill rapidly and reach maximum capacity during the first filling cycle, whereas others take many years to fill.

Due to the lack of local earthquake data before and during the first stages of the reservoir filling, it was not possible to determine exactly when low magnitude earthquake activity may have started if the influence of the reservoir water level is taken in consideration. The area of activity did not affect by water level of the reservoir before 1975, except some few events [3]. Although the exact time of the initiation of the seismic activity can not be determined, it appears that low magnitude activity may have occurred near the reservoir after the reservoir filling. Figure 4, shows the relation between the water level fluctuation in the reservoir and Seismicity from the period 1981 to 2010.

Relation between shallow and deep seismicity and water level in the Aswan High Dam Lake can be observed in the period from 1981 to 1985, 1987 and from 2007 to the end of 2010 whereas it is not clear between these periods.

Daily rate of changes in the reservoir water level and the occurrence of shallow earthquakes along the Spillway fault (about 4.5 km to the north-west of the High Dam) during loading and unloading seasons through the period from 1982 to 2010 are investigated and illustrated in Figure 5.

Table 1: Aswan seismic velocity model

Depth (Km)	P-velocity (Km / sec)	S-velocity (Km / sec)
0.0	4.0	2.3
0.5	6.0	3.4
05.0	6.8	3.9
20.0	7.5	4.3

Focal Mechanisms: Previous studies in Aswan region dealt mainly with the composite focal mechanism solutions. The procedure of determining this composite solution is based on an assumption that the focal mechanisms for the earthquakes are identical. However this assumption may be not true because the stress and strength in the Earth's crust are spatially heterogeneous [20]. In this study, the composite focal mechanism of earthquakes for shallow and deep seismic active zones was determined using the polarities of the first P-wave motion on the Aswan seismic network records. These data are plotted on lower focal hemisphere using software developed by Suetsugu [20]. The field stations of Aswan network are well distributed around the study area. The take off angles were calculated using the Aswan seismic velocity model (Table 1) as determined by Woodward-Clyde Consultants [11].

Table 2: Focal mechanism parameters for the selected earthquakes

Zone No.	Zone	Plane (1) AZ.	Dip	Plane (2) AZ.	Dip	P-axis AZ.	Pl.	T-axis AZ.	Pl.
1	Khor El Ramla (Shallow Zone)	87	78	355	81	311	02	41	02
2	Gebel Marawa (Deep Zone)	75	85	345	89	300	03	30	03

Abbreviations: AZ is the azimuth; Pl is the plunge in degrees.

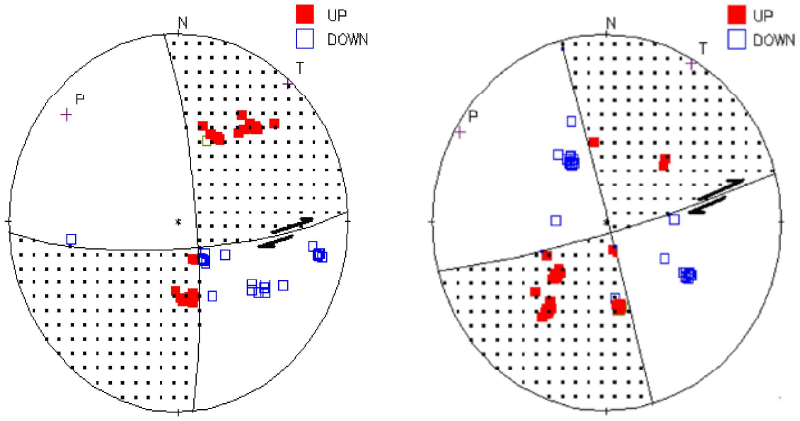

Fig. 6: Composite focal mechanism for shallow and deep earthquakes at Khor El Ramla and Gebel Marawa zone. P and T are the inferred axes of maximum compression and tension. Double arrows indicate the sense of shear displacement on the plane that was chosen as a fault plane.

The solutions of two events at different places are shown in figure 6. The focal mechanism results of these events are listed in Table 2.

According to figure 6, the focal mechanism for two events west of the High Dam Lake are almost pure strike-slips faulting on nearly vertical fault planes with minor normal component. The rupture planes are trending WSW-ENE to NNW-SSE.

CONCLUSIONS

A review of reservoir triggered seismicity in southern Egypt shows that it mainly occurs and located in and near active faults. Instrumental recordings have indicated continuous microseismic activity with the current local events registering more than 4.0 on the Richter scale. They have been shown that the earthquakes concentrated in the west side of the Aswan High Dam Lake with focal depths ranging from one to thirty km. The main concentration of seismic activity being at greater depths beside Gebel Marawa with shallow and less active zone of earthquakes east of Marawa along the Kalabsha fault and scattered within the central reservoir area. The shallow earthquakes are clustered at the intersection of the Seiyal fault with the Kurkur fault anout 40 km southwest of the Aswan High Dam. The depths of these earthquakes ranged from 2 to 7 km. The other shallow events are in and around Spillway fault and along the old Nile Channel and also, parallel to the Gazelle fault South of Kalabsha.

Behavior of the water level in Aswan Lake characterized by a special manner that is the unloading season extends to July or August and the loading season starts to reach its maximum in October or November every year. The sudden increases of the seismic activity and occurrences of some events with high magnitude was first identified and related to the influence of the reservoir water level fluctuation. The shallow earthquakes are in a better correlation with the water level fluctuations in the Aswan Lake than the deep events. Thus, the shallow events may be classified as seismicity induced by water reservoir. Also, this study suggests that the general correlation between deep earthquakes and the tectonic setting is observed clearly in the area with the presence of the Lake Aswan reservoir. Composite focal mechanism for shallow and deep events at different seismic zones west of High Dam Lake show strike slip faults with minor normal component. The P (pressure) and T (tension) stress axes are trending ESE-WNW and NNE-SSW respectively. The Kalabsha fault zone is a right-lateral strike slip fault that consists of several fault segments trending in the east-west direction, perpendicular to the axis of the main course of the Lake Aswan.

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