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Evaluation of recent crustal deformation and seismicity in spillway fault area, Aswan, Egypt

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ABSTRACT

The High Dam is a strategic and vital installation because it is considered as the water strategic tool for Egypt. The dam plays vital role in mitigating risks of water shortages and floods. The body of the High Dam established on the basement Granite. The area around High Dam is suffering from seismic activities starting from the famous earthquake of 14 November 1981 (5.6 ML) southwest of the High Dam. On 7 November 2010, earthquake of magnitude 4.6 ML occurred at Spillway fault. Spillway fault is NNW-SSE trend. The fault was plotted by the High and Aswan Dams Authority and Soviet geologists as a normal fault. The fault is exposed as vertical on the cross section, but perhaps dips steeply to the west. This work is trying to study the stability of the area and its relation to the dams as well as estimating the horizontal displacements. For monitoring the horizontal movements, a local geodetic network consisting of 11 geodetic stations was established. A geodetic results showed a post-seismic deformation zone between the High Dam and Aswan Dam that resulted from 7 November 2010 earthquake occurring at Spillway fault and a distance of 4.5 km northwest the High Dam.

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KEYWORDS
The spillway fault; seismicity; geological and structural setting

1. Introduction

The spillway fault is located at a highly deformed area. The fault was plotted by the High and Aswan Dams Authority and Soviet Geologists as a normal fault (WCC Woodward-Clyde Consultants 1985). In and around this area, many communities (such as Aswan Low Dam Reservoir (1902) and the High Dam (1970) were established and built. The forces affecting both the High Dam and Low Dam Reservoir must be identified using the recent scientific techniques. Consequently, geo-environmental hazards assessment is importantly needed. Accordingly, characterisation of geological structures (e.g. faults) is prerequisite for development foundation (Figure 1). In terms of engineering hazard, the prevailing factor is usually related to the frequency of moderate size earthquakes over short distances. Therefore, it is an urgent engineering issue to recognise the effect of fault rupture risks on mega constructions. We will use a combination of geophysical methods and spatial geodetic techniques to do such work in the area under study.

2. Location and physiography

The research study area measures approximately 65 km2 and stretches for approximately 12 km northward from Aswan High Dam and Nasser Lake on the southern border (Figure 2). It is bordered by the Nile River valley along its western edge and extends for about 6 km towards the west direction. The Luxor-Aswan road runs through the study area, also Aswan International Airport lays southwestern part of this area. The research area represents a section of the Nubian Plain that stretches from Nile in the east to the Sinn El-Kaddab scarp in the west. The surface of this plain in Nile Valley is approximately 100–200 m above the Nile floodplain. Valley of Nile River is situated along the eastern edge of the Nubian Plain; the current valley of Nile occupies canyon carved during the Late Miocene period when, as a result of the evaporation of the Mediterranean Sea, the base level of the proto-Nile River dropped. Remnants of upper part of the ancient canyon form the new narrow valley and steep-sided bedrock canyon in Aswan region that have been cut down into both sandstones of Nubia and basement complex of Precambrian.

3. Geological and structural setting

Knowing the geology of the region of interest is vital in exploration work, as it helps in the interpretation of the measured geophysical data. Field investigation has been focused on collecting structural data along the spillway fault. By recording both position and geometric parameters of such a fault, field-work was completed. The oldest outcropping units are represented by the Precambrian basement rocks. Exposures of basement rocks consisting of igneous and metamorphic rocks belonging to Precambrian age discovered mostly east of the Nile River and occasionally on

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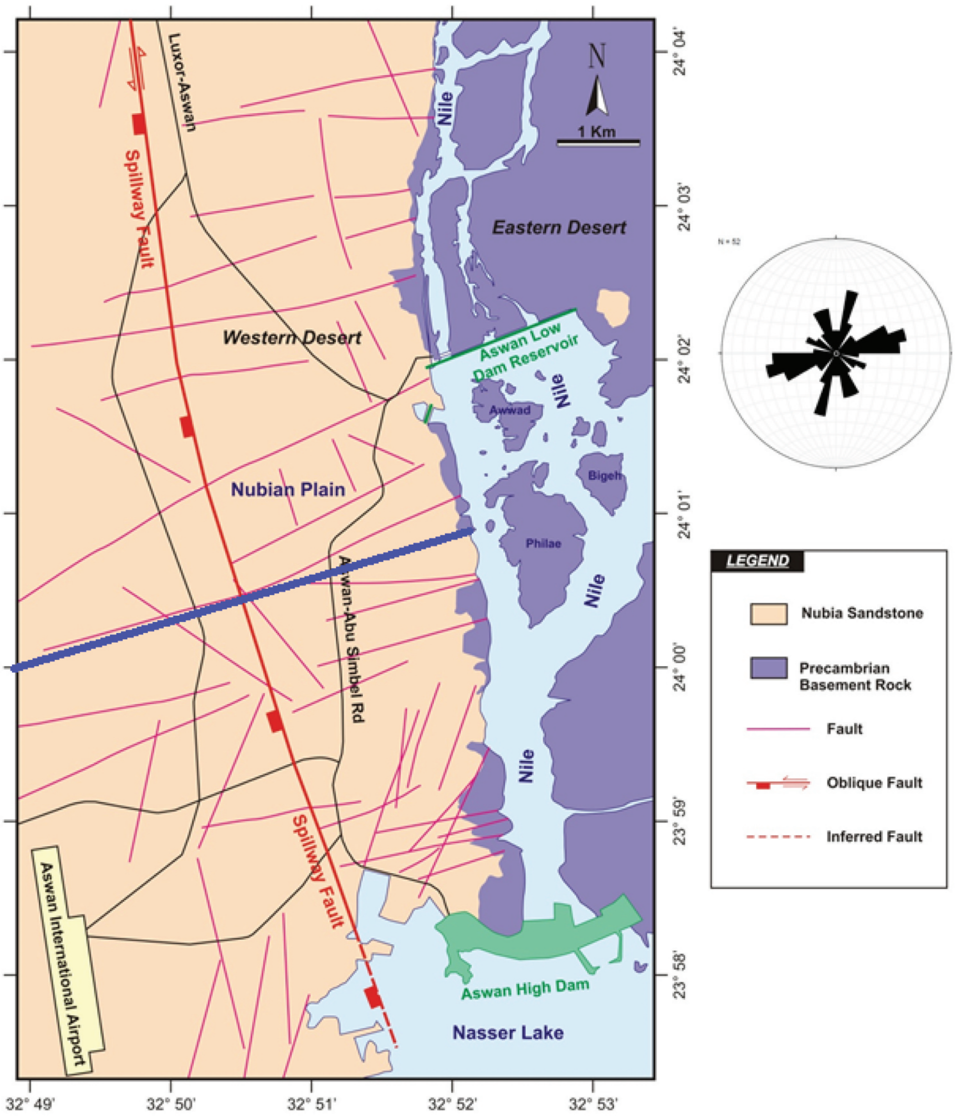

Figure 1. Structural map with rose diagram of the mapped faults attitudes around High Dam area (Abdel-Monem 2020).

the western bank of the Nile. In the Aswan area, the sedimentary column begins with Cretaceous Nubian sandstone, which is considered to be the oldest exposed sedimentary unit and lies uncomfortably above the basement complex (Issawi 1978). The Nubian sandstone is represented by the Abu Agag Formation (Fluvial sediments possibly directly overlying the Precambrian basement of the Turonian age) in the study area (Greiling et al. 1994). It is made of ferruginous sandstone, sandstone and clays. The spillway fault form and geometry were calculated and put on the map in its correct position. The results revealed that the spillway fault strikes towards the NNW-SSE direction (Figure 1). It starts from Nasser Lake with N20°W (340°) strike value and the strike change to be N8°W (352°) where the fault facing Aswan reservoir. The dip value of the fault has a steep angle (about 80°). Such fault shows a sinistrality (left-lateral) movement with a dip component of normal displacement towards the WSW direction. Topographic evidence of normal displacement across the spillway is clear from investigation of the fault scarp as well as the studies of the Digital Elevation Model. Figure (3) shows a topographic profile (XY), which passes across the spillway fault. This profile that was extracted from the ASTER GDEM shown in the Figure (1). The topographic profile shows an elevation difference which reaches 40 m across the spillway fault.

4. Seismic activity

As revealed by a long documented past, the historical earthquake activity within Aswan area is characterised by a low level of seismic activity. Earthquakes in this area could only be identified for more than 4000 years before 1900 on the basis of historical records of damage to towns, temples and tombs, augmented by felt reports independently of damage (Simpson et al. 1987). In the Aswan area, the largest historical earthquakes likely to have occurred did not appear to have

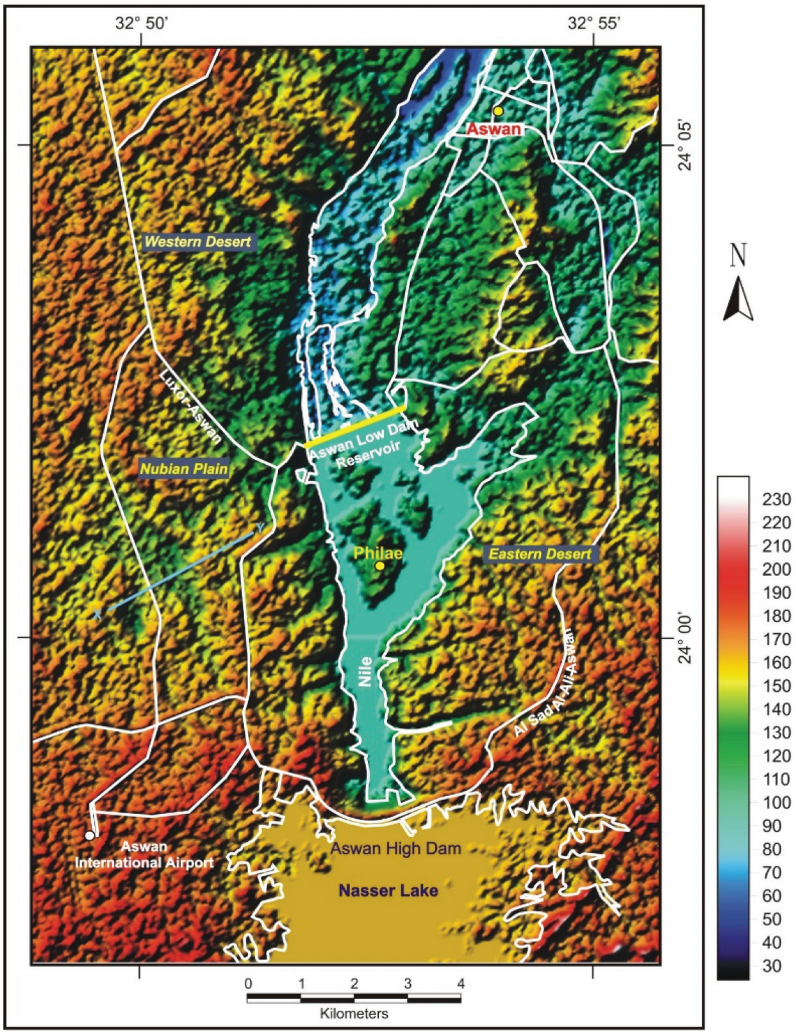

Figure 2. The physiography of High Dam area. ASTER GDEM (15 m resolution).

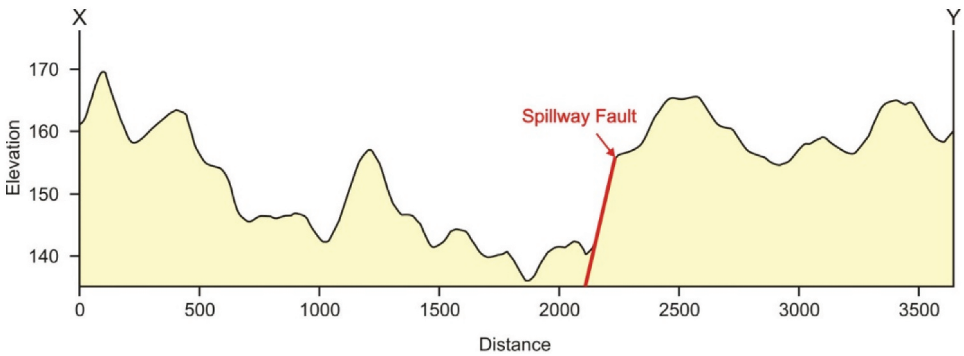

Figure 3. A topographic profile across the spillway fault. For location see the Figure 1.

exceeded a magnitude (Ms) of approximately 7.0 (Kebeasy et al. 1987a). The seismicity trend in the Aswan area shows that the transition zone varies from the higher seismicity level within the Red Sea to the lower seismicity level in the Western Desert west of the Nile Valley (Kebeasy et al. 1981). Within the region of Aswan, with a magnitude of 5.5 and greater, there have possibly been eight earthquakes since about 200 B.C. Since the 27 B.C. incident these have taken place over an average period of 300 years (Kebeasy et al. 1987b). The International Seismograph operations and data analysis began in 1900 and the Aswan region's earthquake coverage became more uniform but remained at a magnitude of about 4.5 levels. Recently the seismicity studied be many authors on the area (e.g. (Awad 2002; Stein and Wysession 2003; Abdelmonem 2006; Abdelmonem et al. 2011, 2012; Deif et al. 2011, 2011; Telesca et al. 2017; Saadalla et al. 2020)). The High and Aswan Dams Authority (HADA) and National Research Institute of

Table 1. The earthquake parameter.

Y	M	D	h	m	sec	Lat	Long	Depth (km)	Mag
2010	11	7	9	54	34.15	24.00°	32.85°	2	4.6

Astronomy and Geophysics (NRIAG) established a local seismological network around the High Dam and Nasser Lake after Kalabsha earthquake on 14 November 1981. On 7 November 2010, an earthquake of magnitude 4.6 M_L occurred at the spillway fault (Table 1). Studies have shown that the epicentre of the earthquake occurred 4.5 km northwest of the High Dam on the spillway fault in the area between the High Dam and Aswan reservoir (Figure 4). Figure (4) show spatial distribution of the earthquakes recorded from 1982 till 2020 in the spillway fault area. Figure (5) shows the cracks of epicentre of 7 November 2010 earthquake.

The fault plane solution of the 7 November 2010 earthquake using the first motion of the P-wave shows normal fault with a minor strike-slip component (Figure 6) (Suetsugu 1995). The plane that strikes NNW is considered to be the fault plane because it fits with the strike of the observed cracks in the epicentral area. Very clear surface cracks were observed in the epicentral area west of the spillway fault and also west of the determined location of 7 November 2010 earthquake (Figure 4). The Egyptian government funded the construction of the National Seismic Network (ENSN), which covers the entire Egyptian territory. Now ENSN consists of 70 seismic stations. ENSN can now detect the majority of the local and regional earthquakes as well as the tele-seismic events (Figure 7). Figures (8 and 9 show spatial distribution of the earthquakes recorded from 1982 till 2020 in Aswan region.

5. Geodetic technique for monitoring the recent crustal deformation

The study of recent crustal deformation is important to study the stability of the region and to know the effect of the change in water loading on the stability of the regions around the reservoir. Monitoring the pattern of deformation is also one of the most effective ways of determining the basis for the safety status of such structures. The safety management of dams is therefore focused on the study of their structural behaviour, based on the monitoring of a broad range of variables, defining and corresponding stresses. Dam safety regulation depends on the study of its structural behaviour, which is based on earthquake monitoring and recent crustal deformation. Due to its direct effect on the body of the High Dam and its protection, the study is very important for the General Authority of the High Dam as it will provide decision-makers with the knowledge resulting from the results of the study. An available data (2009 to 2019) from the local

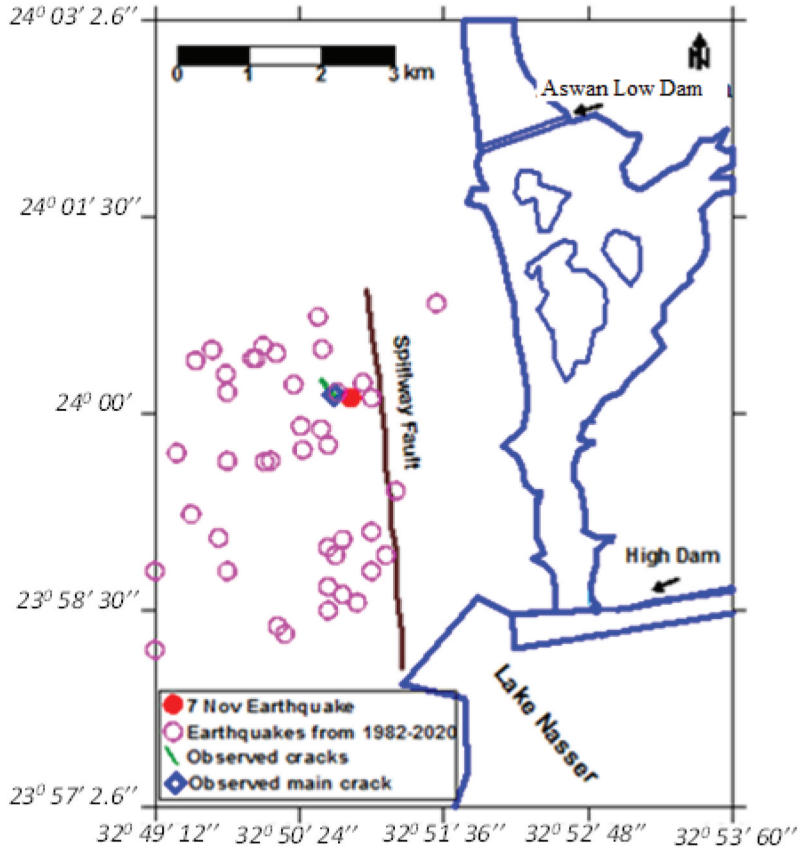

Figure 4. Close view of the spillway fault area shows seismicity from 1982 to 2020.

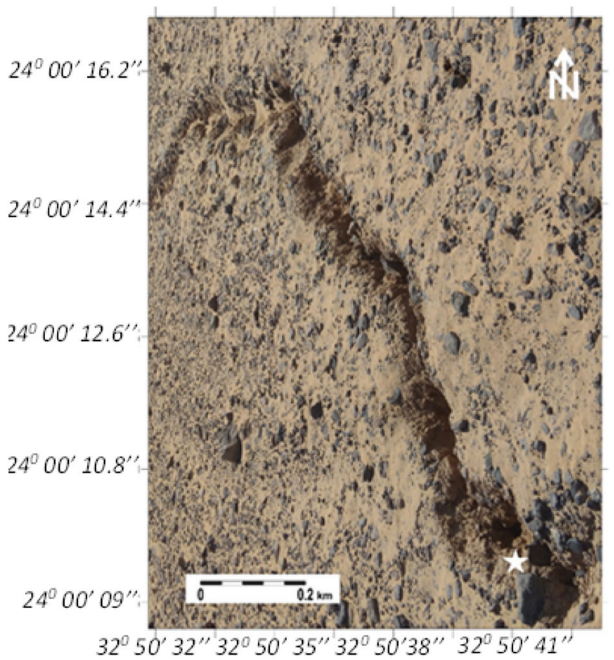

Figure 5. Surface cracks observed west of the determined epicentre of 7 November 2010 earthquake and west of the spillway fault.

geodetic network which covering the entire region was collected to assess the recent deformation (Figure 10). The geodetic data was analysed between 2009 and 2019. Baseline analysis processing was done using Bernese software version (5.2) (Dach et al. 2015) and deformation estimation programmes. The sampling interval and elevation were set at 1° and 5°, respectively, during the survey. In the measurement of the baselines, the International Geodetic Stations (IGS) ephemeris was applied. In order to calculate the precise coordinates of all network stations in the International Terrestrial Reference Frame (ITRF, 2014), the network is connected to IGS. Under the assumption of free network modification, the displacement vectors at each geodetic station were calculated. The horizontal components at each station were determined from the difference between the stations coordinate changes. From the coordination shifts, the displacement vectors were determined. Most of these displacement vectors can be primarily attributed to the movement within High Dam region in those measurement campaigns, taking into account the trust limit. In the diagram, the horizontal elements of the displacement vectors are shown (Figure 11). The error ellipses here represent normal error in all directions around the position observed. The major horizontal changes over the time of observation are recorded by all stations of the network. The magnitudes of the motions are distributed over this region inhomogeneous. For determination of interpreted displacements of horizontal motions, initial displacements at the stations in this network were used.

For the calculation of strain tensor parameters, the horizontal components of the displacement vectors are used: dilatations, maximum shear strains and principal strain axes are calculated during the observation periods. The strain tensor is the software used to measure these parameters. The region under analysis was divided into four blocks according to the distribution of the geodetic points in order to compute the deformation parameters. The parameters of deformation are related within the network to the centre of a single block. The strain parameter values are very small and not important. Figures (12, 13 and 14) indicate, respectively, the approximate dilation, maximum shear strains and total strain. These values are relatively small and non-significant at times. In the High Dam area, they may well depict features of crustal deformation. This means that the rate of deformation in this region is very low, with the exception of the high deformation rates in the area of the emergency spillway. During the current interval, the rate of strain accumulation is relatively small and is categorised into

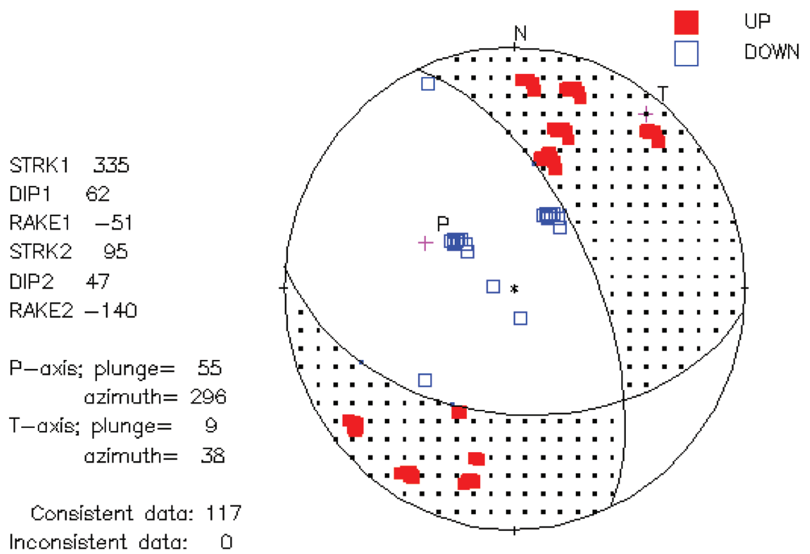

Figure 6. Fault plane solution of the 7 November 2010 earthquake using the first motion of the P-wave.

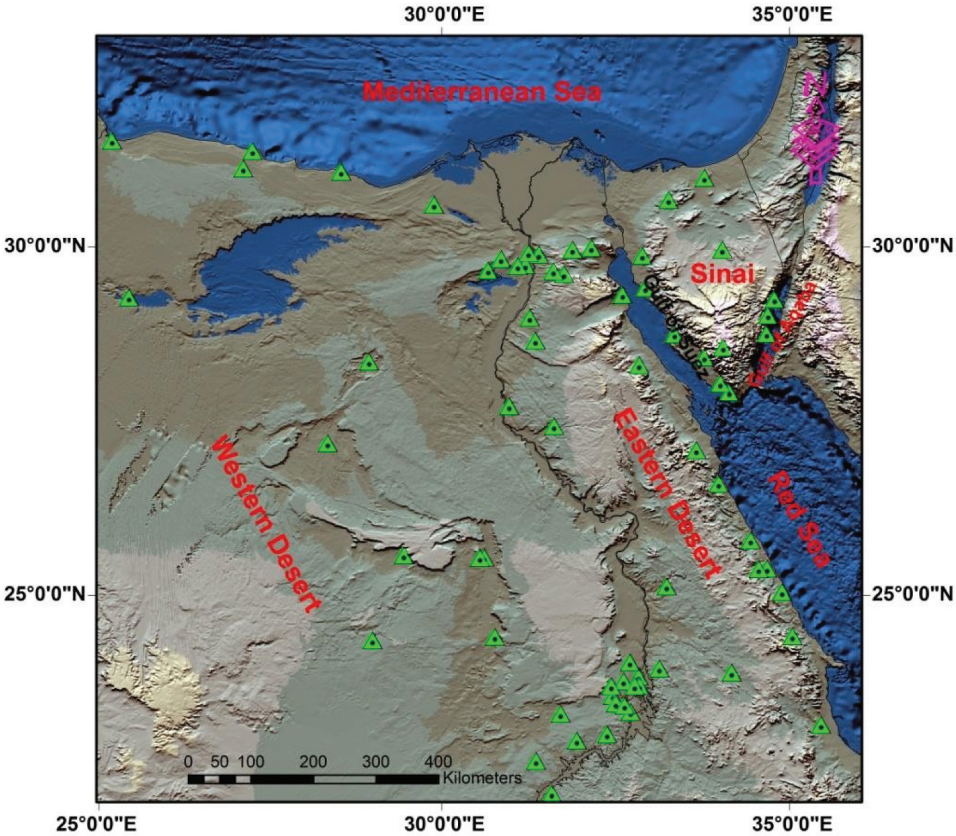

Figure 7. Distribution of the ENSN stations.

the lowest strain classification group. Magnitudes and orientation of key strain rate axes across four network blocks were measured and graphed in the Figure 15. This is an unbalance of the forces of all blocks between compression and extension. The results of these studies reflect the framework of the dynamic deformation model that has taken place in the region under investigation. Studies of the movements of the crust movements are known to involve a large amount of data spread over a large period of time. Analysis of the time changes of movements over the ten years from 2009 to 2019 was measured in the present work. For all years until the year 2019, the cumulative movements from the year 2009 to the required year were determined. From the statistics, it is obvious that most points shift in the same manner, direction and form. This suggests that most of these motions are due to the displacement of the global tectonic plate and are not a cause of stress in the area (Figures 16 and 17).

6. Precise levelling measurements to determine vertical movements

Four levelling lines "Profiles" were established to cover the active part of the spillway fault to determine the vertical movements (Figure 10). Three of them are perpendicular to the spillway fault and the fourth is parallel to it. The measurements of levelling lines were carried out and will are repeating regularly. The precise automatic level device, "Sokkia (SL1x_01)", invar rods with a metallic cover of 3.0 m length and heavy footplates (4.5 kg) were used. Levelling measurements designated as first-order in double run, i.e. the measurements of difference in heights were performed twice, forward, and backward measurements. The measurements at all stations were carried out continuously without interruptions forward and backward. The differences between backward and forward measurements in section can serve for estimation of the accuracy of levelling. Least square adjustment was used during analysis of the interval of levelling data, parameters of heights and rates of vertical movement were estimates. The vertical changes along the levelling lines are shown in the (Figure 18), which represents different subsidence in some benchmarks and uplift of the other. This Figure indicates that, the area is divided into two parts: subsidence in the western part and uplift in the eastern part. This result of the vertical analysis is supported by the analysis of the horizontal movements.

7. Summary and conclusion

The geologic study included review of the regional tectonics and geologic framework, geomorphological and physiographic analyses, rock unit's distribution and geologic structures analysis. The geologic study

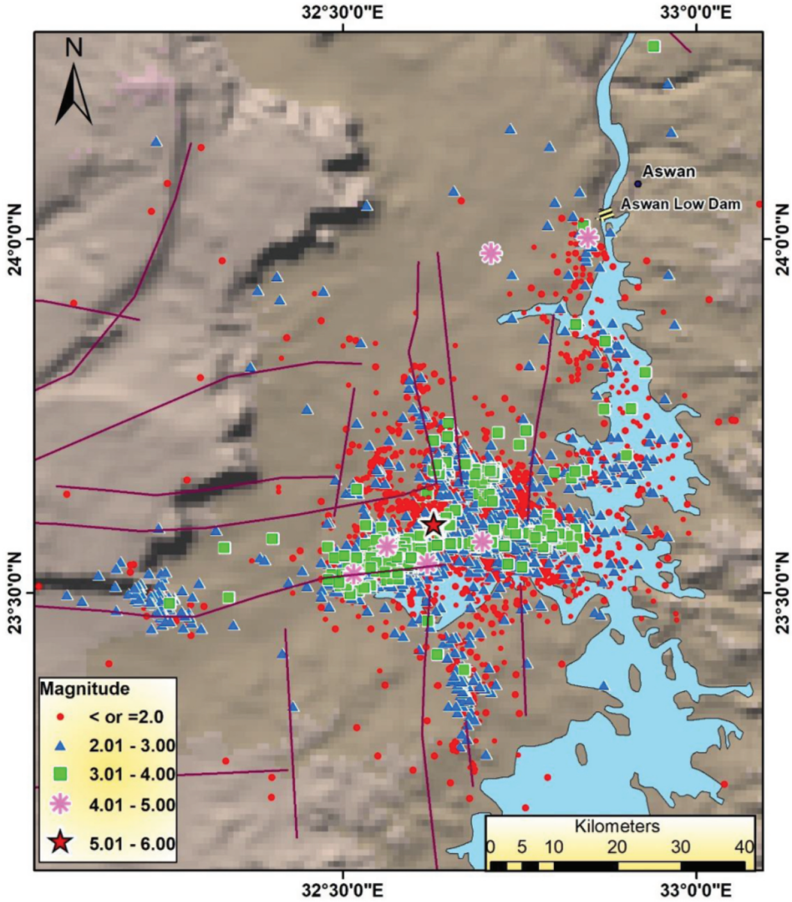

Figure 8. Seismicity map of Aswan region (1982–2020).

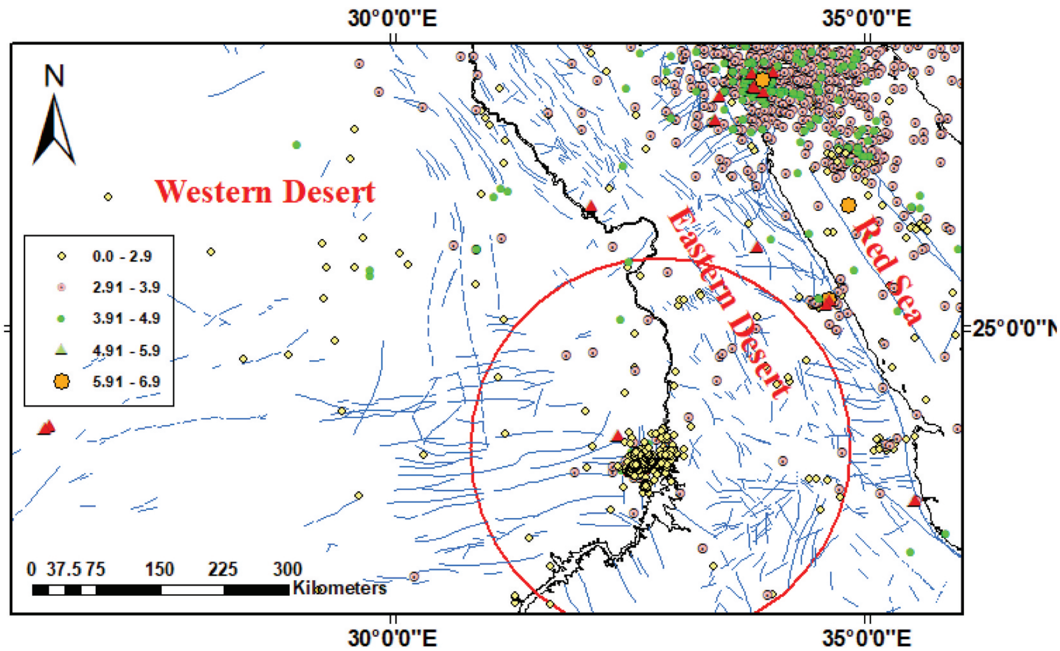

Figure 9. Distribution of the earthquakes in the compiled catalogue.

identified some surface faults at the eastern and western banks of the River Nile at the site under investigations. The fault trace of the channel fault is inferred based on the surface features. From the results of the geophysical survey, it was confirmed that there are two zones of cracks, which are considered a weakness region in the sub layers of the area beneath the spillway fault from the eastern and western sides. These are two zones of cracks extend to the spillway floor region. The continuous seepage and presence of water inside the cracks leads

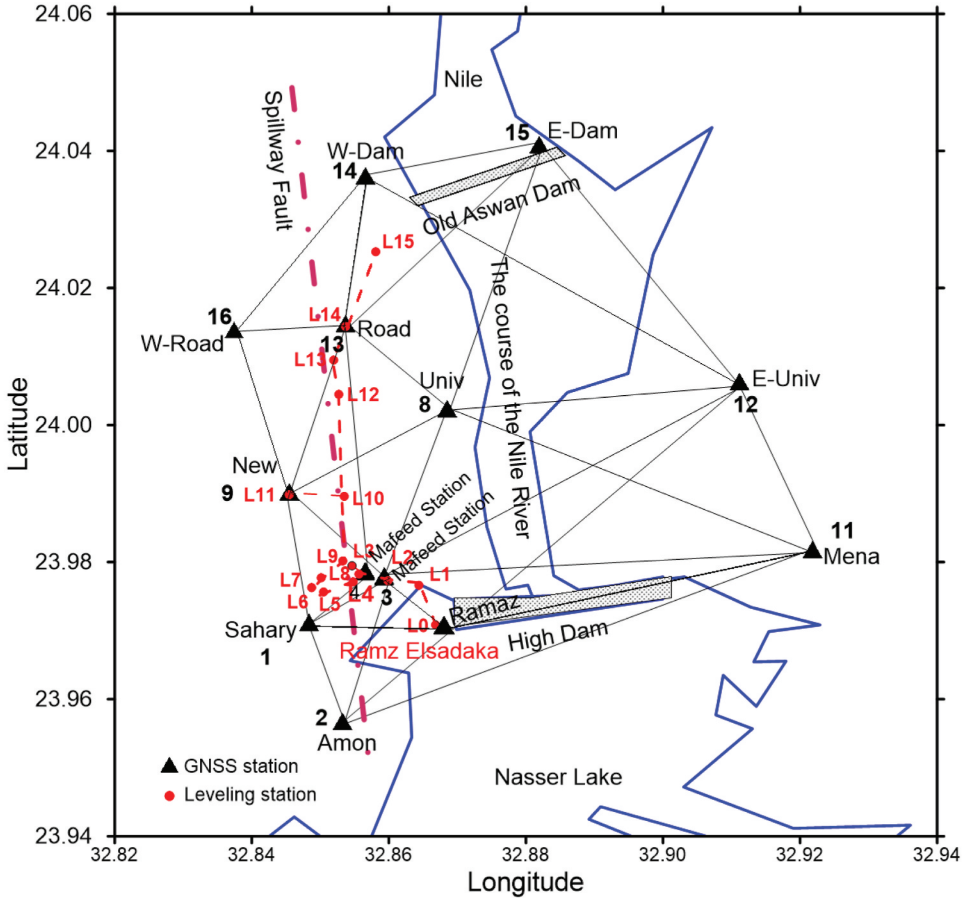

Figure 10. Geographic location of the High Dam geodetic network and precise levelling profiles.

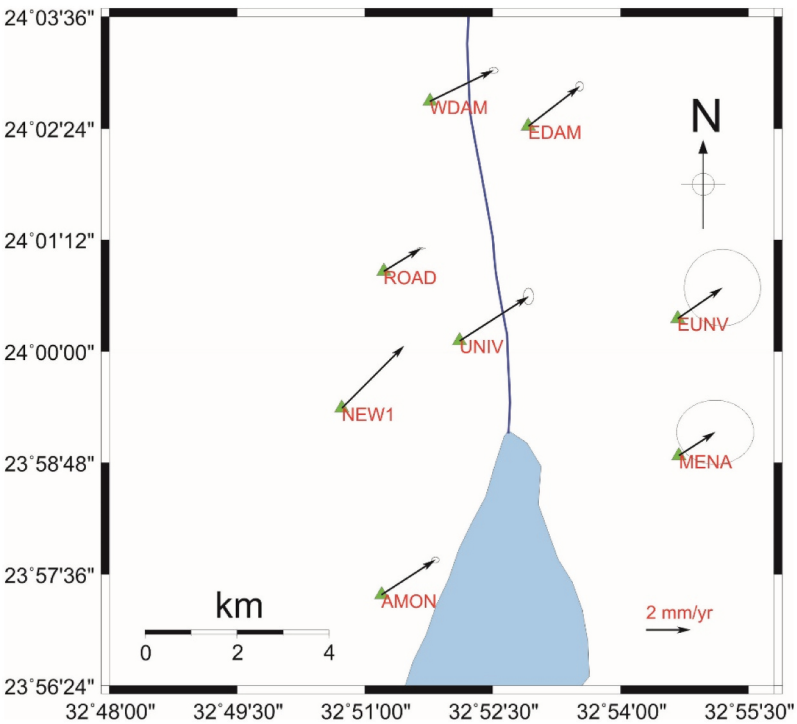

Figure 11. The magnitude and direction of the horizontal displacement of the High Dam geodetic network points from 2009 to 2019.

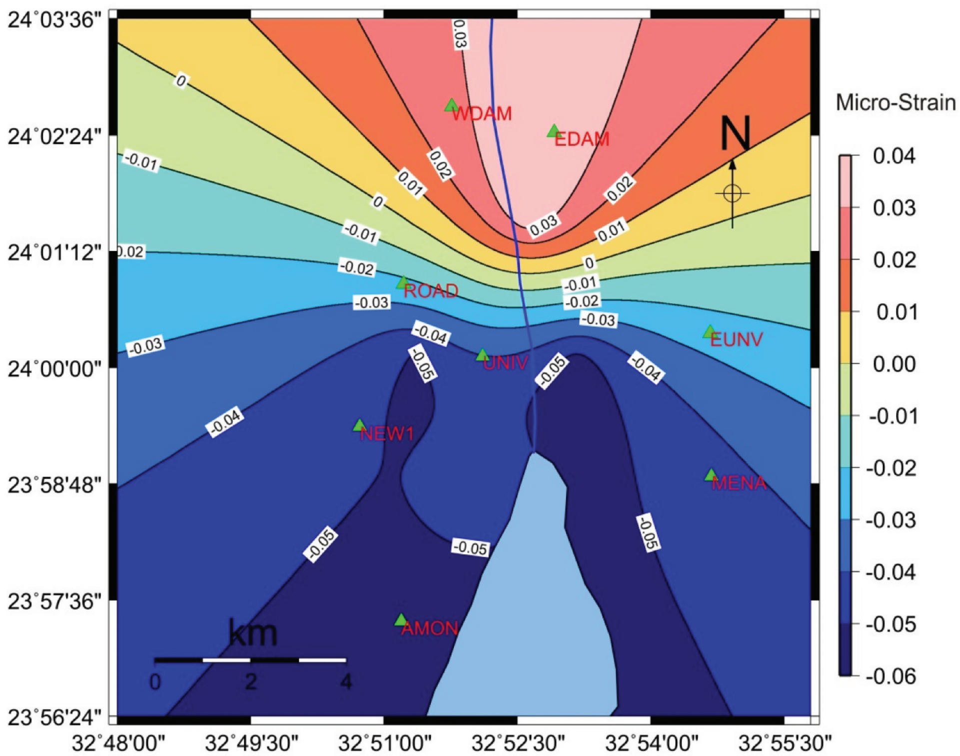

Figure 12. Distribution of dilatation strain rates for the period from 2009 to 2019.

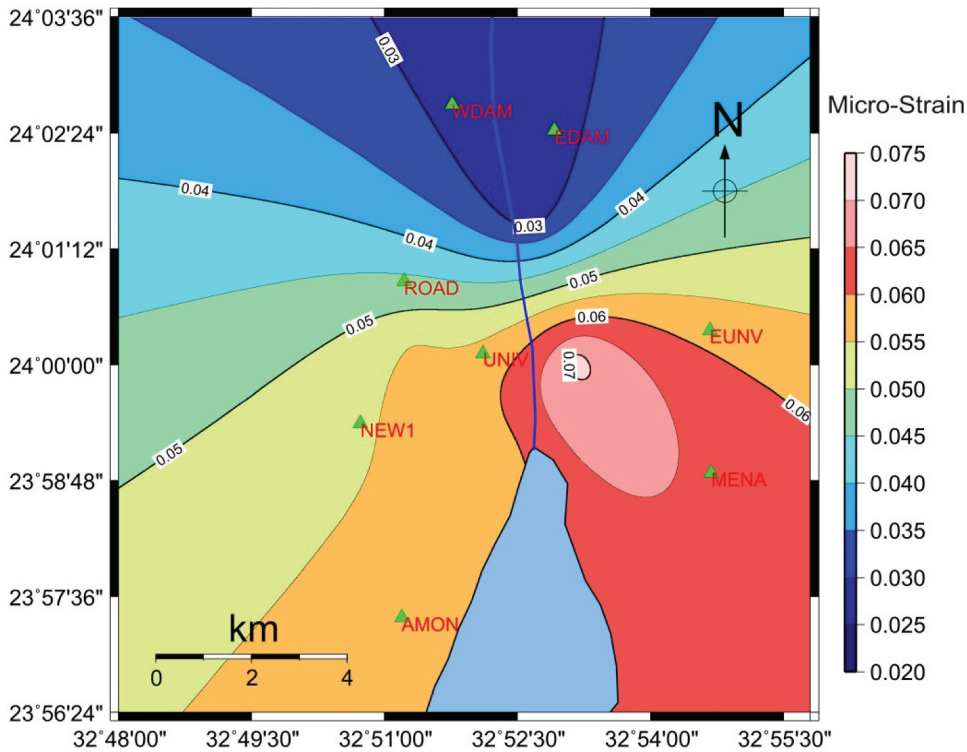

Figure 13. Distribution of shear strain rates for the period from 2009 to 2019.

to their expansion, which affects the body of the dam particularly in terms of the spillway shoulders near these cracks. The continuous seepage and presence of water inside the cracks leads to their expansion, which affects the body of the dam particularly in terms of the spillway shoulders near these cracks.

On 7 November 2010, a 4.6 magnitude earthquake struck about 4.5 kilometres northwest of the High Dam, in the region between the High Dam and the Aswan Low Dam Reservoir west of the spillway fault. The movement along the fault has been defined as natural faulting by the High and Aswan Dam

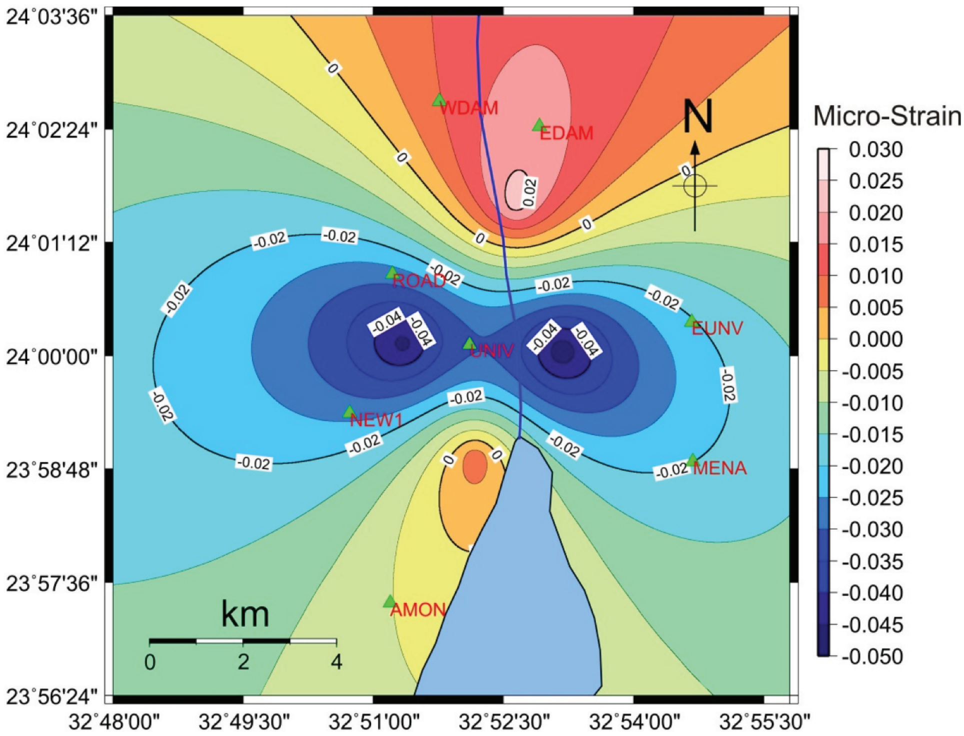

Figure 14. Distribution of total strain rates for the period from 2009 to 2019.

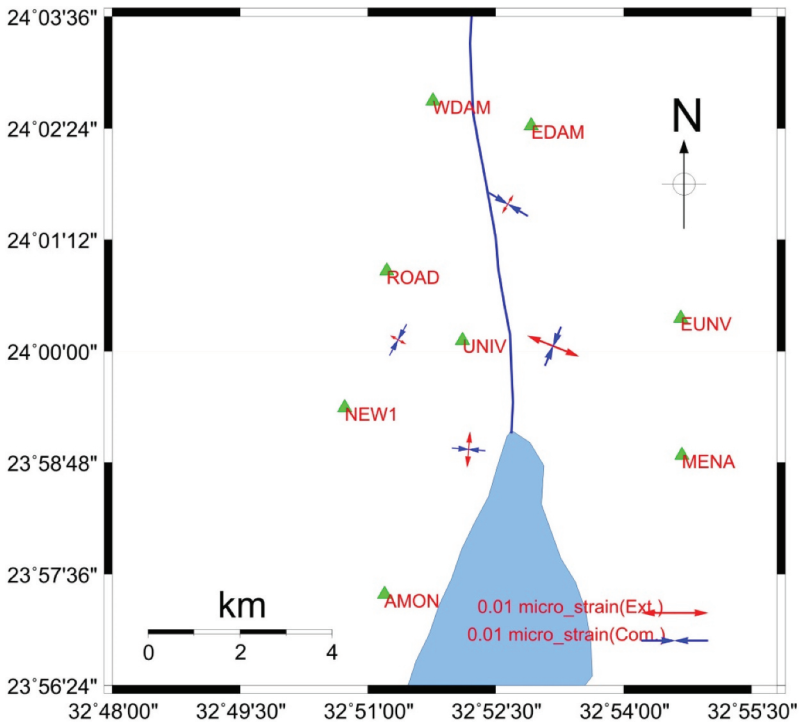

Figure 15. The main strain element computation of the High Dam geodetic network during the period from 2009 to 2019.

Authority (HADA) and Soviet Geologists. The absence of dike displacement, according to (WCC Woodward-Clyde Consultants 1985), means that the fault is not a lateral-slip fault. They also mentioned that the spillway fault has no bearing on the High Dam's seismic hazard assessment. Using the first motion of the P-wave, the fault plane solution for the 7 November 2010, earthquake shows a regular fault with a slight strike-slip portion. The recent records of the Egyptian National Seismological Network (ENSN) and Aswan Seismological Center (1982–2020) do not show seismic activity at the fault beneath the water channel. But it does not mean that this fault will not produce earthquakes in the future.

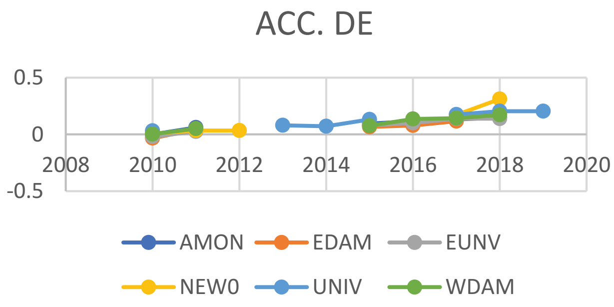

Figure 16. The magnitude and direction of the cumulative change in metres in the east direction of the points of the local High Dam geodesic network. During the period from 2009 until October 2019 in the International Terrestrial Reference Frame (ITRF) 2014 coordinate system.

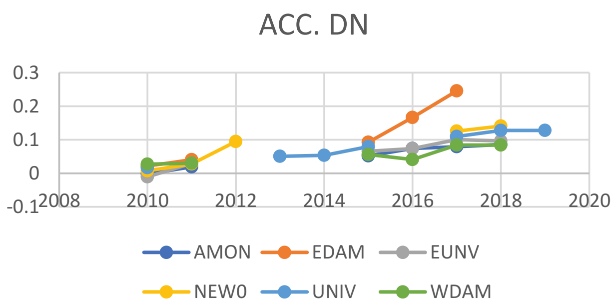

Figure 17. The magnitude and direction of the cumulative change in metres in the north direction of the points of the local High Dam geodesic network. During the period from 2009 until October 2019 in the International Terrestrial Reference Frame ITRF 2014 coordinate system.

To evaluate the key characteristics of the deformation and hazard estimation for the given region in the High Dam area, results from the data sets are compared and combined. Data processing is performed using the latest specialised programmes and mathematical models in order to reach the required accuracy and the desired goal. The horizontal displacements were determined of the area associated with the occurrence of earthquakes. The results of horizontal and vertical movements of the High Dam network indicate that there were no significant changes during monitoring period except for the emergency spillway area that suffered from high deformation rates. The magnitude of the movements is distributed as an inhomogeneous over the area.

The accumulated strains indicate that, the area is divided into three areas: western and eastern parts of the spillway fault and the around of the Aswan low Dam Reservoir areas where compression strains are predominant and the middle part where extensive areal strains prevail. In the southern and northern parts, the areal compressions strains are found to be about 0.2 ppm/yr. On the other hand, the large area of extensional strains is found in the middle part of the studied area. The extensional strains in this area found to be about 0.4 ppm/yr. Maximum shear strains show some patches of high values of strains in the middle part of the western bank between the two dams. On the other hand, the eastern bank showed a low strain.

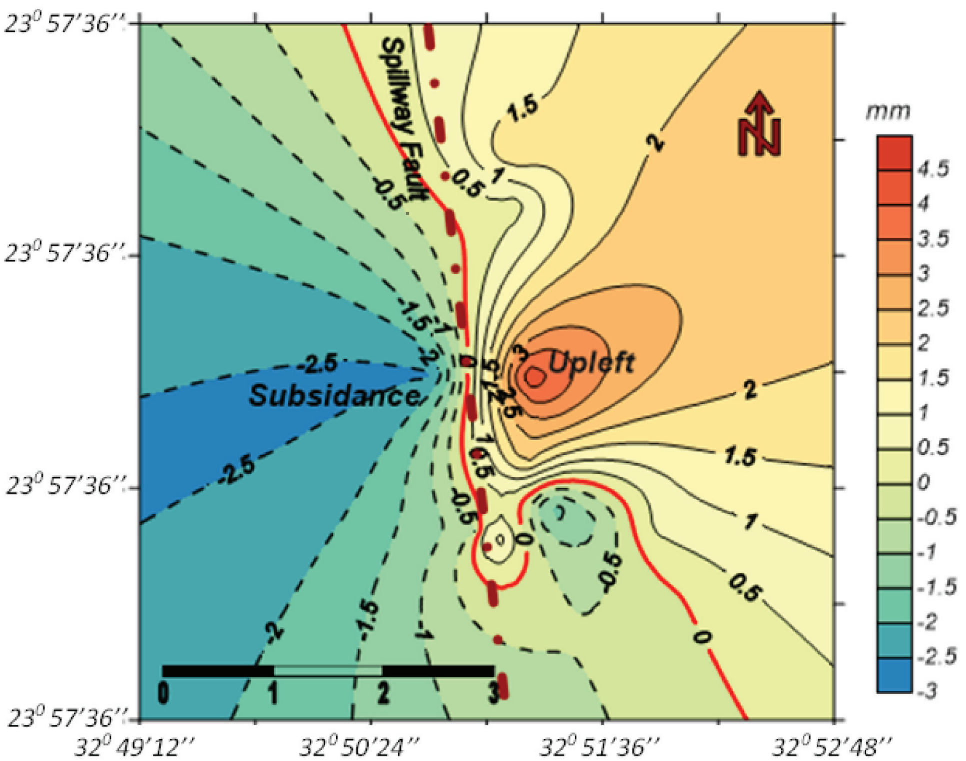

Figure 18. Distribution of the rates of vertical crustal movement in area between the High and old Aswan dams for the interval 2019–2020. The values are in mm/yr.

There is some balance between extension and compressive forces in some blocks. The results of these analyses represent a framework of dynamic model for the deformation occurred in the High Dam area.

The time change of the movements was studied over the ten years from 2009 until 2019. The grouped movements were calculated as it is evident that most of the points move in the same manner, direction and general shape, which confirms that most of these movements are a result of the movement of global tectonic plates and do not represent a source of stress in the region. The subsidence was recorded in the western part and uplift characterised the eastern part of the spillway fault zone. This finding is consistent with the low number of earthquakes that occurred in the area during this time.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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