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Crustal displacement accompanying earthquakes activities in Egypt

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ABSTRACT

In Egypt, there were many earthquake activities in seismo-tectonic regions. In the last century, most earthquakes concentrated in the Gulf of Suez and the Gulf of Aqaba. Also, Egypt was affected by large earthquakes in the northern Mediterranean Sea. In this study, we are trying to evaluate the crustal displacement associated with large earthquake activities by using GNSS measurements. GNSS observations can measure the horizontal and vertical displacement within mm of accuracy. Earthquakes with a magnitude of more than 4 have been chosen. The crustal displacements have been computed using GNSS data from the Egyptian Permanent Geodetic Network (EPGN). The results show that before, during, and after earthquake activities, the displacement of GNSS stations gives different behaviors depending on its distance from the earthquake epicenter. In some studied GNSS stations, a signal of deformation before the earthquake was found. This displacement can used in the establishment of an early warning system for earthquakes using GNSS observations.

Keywords: GNSS, Seismic activities, Deformation, Displacement, Earthquake Magnitude

1. INTRODUCTION

Because of the rising number of earthquakes, tsunamis, and volcanoes, there is an increasing awareness that is crucial to figure out the earth's ground reaction level and look into its impact on the movement of the surface measurements. These natural disasters induced motions in the Earth's crust that prompted changes in displacement. A possible benefit of understanding these motions is that they can be used to predict when an earthquake may take place, which helps prevent or mitigate assets and loss of life. The high-precision Global Navigation Satellite System (GNSS) was successfully established and is now increasingly utilized as a result of developments in positioning technology as well as the increasing use of continuous tracking stations [3]. Large-scale observations and monitoring of icebergs, tsunamis, and geodynamics of the earth can be detected by using GNSS observations. Many studies have tried to evaluate the earth's motion during earthquake activities. Rasha et al., (2020) [9] looked into the application of the GNSS method to identify displacement rates at network points near the 2017 Aegean earthquake in Turkey. Furthermore, station deformation of the Aegean network under the seismic aftershock is discussed that transpired three months following the Aegean earthquake. Next, an evaluation of the deformation rates for the geodetic points was conducted over three consecutive days: the day prior, the day of the earthquake, and the day after. It was additionally determined that lengthening the monitoring periods leads to more reliable findings and decreases the likelihood of notable financial and human losses.

Olga et al., (2021) [8] have mapped the seismic deformation related to an earthquake that took place in NW Croatia with magnitude Mw 6.2. Two geodetic tools have been used. Both Interferometric Synthetic Aperture Radar (InSAR) and GNSS observations were analyzed and processed. By integrating the descending and ascending orbits of SAR Sentinel-1, they were able to detect the approximate ground displacement over the region of concern. Illustrations of ground displacement deduced from SAR Sentinel-1 data show the left and right lateral surface deformation behavior. To address the movement related to the earthquake and its structure fault system. Similar results have been observed on the Sisak GNSS station of Sisak, displaying a 3 cm rate of subsidence and a 5 cm horizontal displacement to the southeast direction.

In an attempt to build a model that could be customized to different scenarios, Claudia et al., 2023 [2] looked at the effects of different dataset configurations using the GNSS with high sampling intervals, including some factors such as earthquake magnitudes, station counts, distances from earthquake center and signal durations. From the study, the model's ability to reliably forecast earthquake magnitudes from synthetic data with $0.07 \leq RMS \leq 0.11$ has been determined sufficient.

Zhiyu et al., (2021) [14] estimated the magnitude of the Maduo earthquake that struck in 2021 west of China. GNSS measurements from 55 permanent stations have been used. The results showed that a signal of deformation. The amplitudes of this signal gradually decreased as the hypocenter distance increased. Peak ground velocity (PGV) and Peak ground displacement (PGD) facilitate the rapid assessment of an earthquake's magnitude before the damage, thus rendering them crucial variables for systems of seismic activities early warning.

The integration of SAR data in conjunction with GNSS observations during the largest earthquake in California in July 2019 (Ridgecrest Earthquakes), was investigated by Katherine et al. in 2022 [6]. It is concluded that this GNSS-corrected InSAR time series can be a sufficient tool to study the post-seismic deformation of the earth including aftershocks near from earthquake center and its elastic deformation parameters. By using GNSS and InSAR data the model of deformation that happened with Ridgecrest Earthquakes can be demonstrated.

Lots of moderate and small earthquakes that are distributed throughout multiple source regions frequently happen in Egypt. The structure of the tectonics of Egypt is considered so complicated. One of the main producers of earthquake activities along Egypt is the movement of three main plates African, Arabian, and Eurasian. Most of the population and agriculture activities can be found in northern Egypt. This northern part is deformed by continuous seismic activities. Also, many earthquakes were found along the Red Sea fault and some locally disturbed faults. These earthquakes had a significant impact on Egypt. Therefore, it is important to understand Egypt's seismic activity to reduce risk and danger. Crustal deformation results from the energy released by earthquake activity. Deformation of the crust can be shown as displacement in both vertical and horizontal components. GNSS observations can be used to determine these displacements.

Using GNSS permanent stations started in Egypt in 2006. The establishment of GNSS stations aims to study the crustal deformation along Egypt. In the current work, we tried to estimate the displacement due to earthquake activities in Egypt. Permanent GNSS data was used before, during, and after the chosen earthquakes to compute the displacements.

2. SEISMIC AND EARTHQUAKE ACTIVITIES

Although there have been dangerous earthquakes in Egypt throughout its history, the country is renowned for having low seismic activity. Egypt's seismo-dynamic position shows that major earthquakes may occur, especially near the Gulf of Aqaba–Dead Sea transform, the Subduction zone along the Hellenic and Cyprian Arcs, and the Northern Red Sea triple junction point. A few significant sources located in the Dahshour, Aswan, and Cairo-Suez Districts should also be taken into account. Southeast of the Mediterranean Sea, Egypt is considered to be part of the Eastern Mediterranean region [10]. The Eastern Mediterranean Sea is a small ocean basin that stands out for its distinctive tectonic complexity [14].

Even though Egypt has witnessed some dangerous earthquakes over time, its territory is known for having low earthquake activity. Egypt's geodynamics position reveals that significant earthquakes could happen, particularly in certain three regions: the triple junction point of the Northern Red Sea, the Subduction zone of the Mediterranean Sea, and the Gulf of Aqaba–Dead Sea fault systems. It is also important to take into consideration some other seismic deformation sources that are found in the Dahshour, Aswan, and Cairo-Suez District [12].

Southeast of the Mediterranean Sea, Egypt is considered to be in the Eastern Mediterranean region. Considering the complicated and deep structures of the Eastern Mediterranean area [15]. The Eastern Mediterranean Sea is a small basin distinguished by its independent geological structure. From the study of Stampfli et al. (2001) [11], the Eastern Mediterranean Sea is a remnant of the Mesozoic Ocean and features a small portion of the intersection border between the Africa and Eurasia plates. In this section, collapse develops along the quite small Cyprian and Hellenic arcs. The evolution of the Mediterranean area appears to be the result of crustal compressional deformation deduced from the motion of the African Plate northward relative to the Eurasian Plate.

Most of the earthquakes that generate and dissipate originate in seismo-active zones that continue along the Dead Sea transform (DST), the Cyprian arc (CA), the Hellenic arc (HA), the Red Sea, and the Suez fault [8]. In the north of the Gulf of Suez, seismic activity is declining, meaning that the area continues to be linked to the African Plate [10, 1]. The Dead Sea zone shows a left-lateral strike-slip fault that explains the geodynamic movements of Arabia and Africa. It connects the Taurus subduction zone to the north over a distance of about 1000 km.

From previous geological studies [12], earthquakes extending northward along the Suez Rift include the Cairo to Alexandria region. This trend represents one of the main seismic trends in Egypt, The basis for the trend's activity has been suggested to be caused by two main sources. First is the Red Sea fractures and second is the faults that have NNW tendencies and run parallel to the Eastern Mediterranean Sea, Red Sea, and Gulf of Suez directions (see Figure 1).

Earthquakes with deeper epicenter are mainly found along the Cyprian and Hellenic Arcs that result from the act of subduction between Africa and Europe, while shallow earthquake epicenter is primarily focused near the edges of plates and on some active seismic zones like the Abu Dabbab, Aswan, and Cairo-Suez regions. Some studies distinguish four main seismic trends in Egypt: 1) the Eastern Mediterranean-Cairo-Fayoum; 2) the Northern Red Sea-Gulf of Suez-Cairo-Alexandria; 3) the Mediterranean Coastal Dislocation; and 4) the Aqaba-Dead Sea Transform [1] (See figure 2).

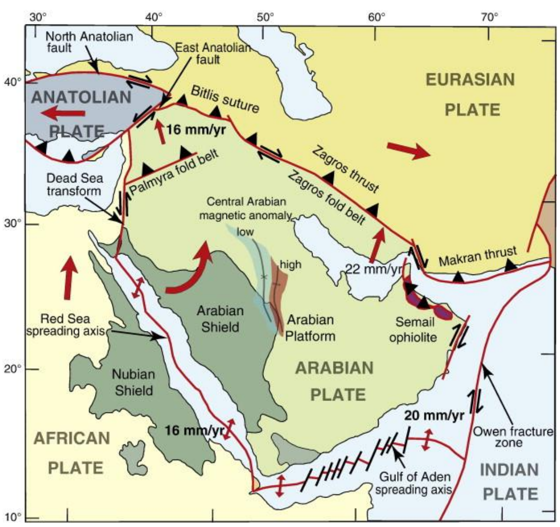

Figure 1: Geodynamics characteristic of Egypt [10].

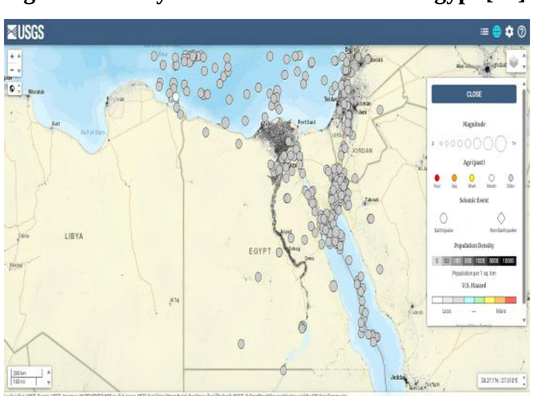

Figure 2: Earthquake activities from 1980 to 2023 from United States Geological Survey (USGS) Magnitude > 4.

In our study, we are trying to find the relation between seismic activities in Egypt and their corresponding deformation.

3. DATA ACQUISITION

The cause of the earth's deformation is different. Some deformation is related to induce seismicity deduced from huge man-made construction such as the case of Nasser Lake induced seismicity. Other deformations are associated with the geodynamic source of earthquake activities. GNSS observations have wide applications in monitoring troposphere and ionosphere parameters. Also, it can be used in monitoring the earth's deformation. The application of GNSS in geodynamics has been the subject of numerous studies [7, 13]. Based on the station coordinates derived from GNSS observations, monitoring the shift in coordinates over time is also a valuable tool for tracking the deformation of the crust triggered by earthquake activity. In this study, we used data from the EPGN network which consists of 26 GNSS stations in Egypt beside The International GNSS Service (IGS) stations. IGS stations have been used for minimum-constrained solutions. The used IGS stations are (ISBA, DRAG, MERS, MATE, NICO, ORID, NOT1, SOFI, and TEHN). So, our geodetic network contains 26 EPGN stations and 9 IGS GNSS stations (see Figure 3.). All GNSS stations are processed together in each daily solution. We chose GNSS observation for days before, during, and after earthquake activities. In our study, we use GNSS data from the Egyptian Permanent Geodetic Network (EPGN) provided by the National Research Institute of Astronomy and Geophysics (NRIAG) (see Figure 3). For IGS stations, data is downloaded from the official site of IGS service.

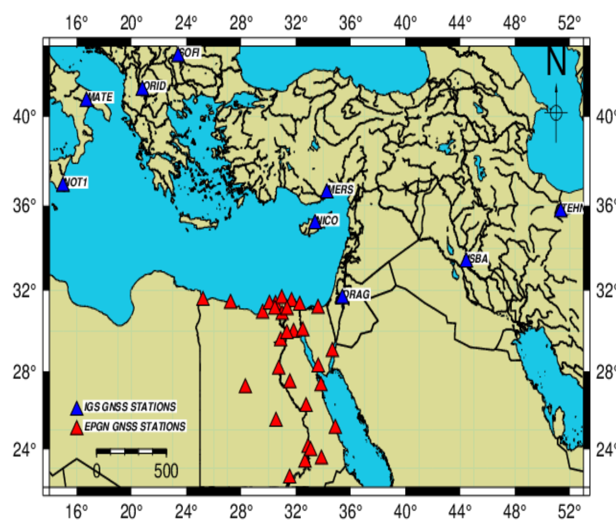

Figure 3: Distribution of the used IGS and EPGN stations.

In addition, earthquakes have been extracted from the USGS catalog. Coordinates behavior before during and after the earthquakes has been studied for many GNSS stations in Egypt. Earthquakes with magnitude > 4 have been chosen for the study. The nearest GNSS stations to the epicenter of the earthquake are used to evaluate the effect of the earthquakes on station displacements. Table 1 shows the used earthquakes and their magnitude.

The workflow for the paper can be summarized as follows:

1- Extracting earthquakes with magnitude > 4 from the USGS catalog for the last ten years in Egypt.

2- Collecting the GNSS data from EPGN and IGS stations for the periods before, during, and after the earthquakes.

3- Processing of GNSS data together and getting daily coordinates for the nearest points from the earthquake epicenter.

4- Time series analysis of the coordinates and behavior of displacements during the earthquake activities.

Table 1. The source parameters of the chosen earthquakes occurred in Egypt with a magnitude >4.

Earthquake	Mw	Date	Location	Depth in km	Distance to nearest GNSS station
1st Earthquake	6.5	2 May 2020	34.182°N 25.710°E	10	620 km from BORG, Egypt, DOY 123
2nd Earthquake	4.5	2 Sept. 2015	30.629°N 28.521°E	47	120 km from BORG station, DOY 245
3rd Earthquake	4.3	1 Feb 2022	29.364°N 31.552°E	10	75 km from KATA station, DOY 32
4th Earthquake	5.5	16 Jun. 2020	27.344°N 34.720°E	10	100 km from HURG, DOY 168

4. DATA ANALYSIS

The GNSS data were processed by Bernese 5.2. The processing includes minimizing the errors in the GNSS system. The processing of GNSS data started from handling and cleaning of observations passing through ifferencing and combination of GNSS signals to resolve the ambiguity. Also, the troposphere and ionosphere models have been applied. The baseline solution generated values for coordinates and errors for baselines, which were then used to calculate the variance-covariance matrix. With a sampling rate of 30-second data, the GNSS data was processed in 24-hour sessions beginning daily at 0:00 UTC. The processing recommendations of the National Geodetic Survey of America (NGS) were utilized [4]. Ionosphere ionosphere-free linear combination was used with an elevation cut-off angle of 5∘. The ephemeris of clocks and satellite orbits earth rotation parameters were used by the International GNSS Service to get highly precise positions. Absolute phase center variations (PCV 2014) were utilized. For each day, one combined solution has been estimated. The repeatability between daily solutions and Root Mean Square (RMS) errors for each coordinate has been computed see Table 3. It is noticed that the mean of RMS is less than 1 mm. Also, the repeatability ranges from 1 to 3 mm in horizontal and up to 4 mm in vertical.

For baseline creation, the OBS-MAX strategy was applied which depends on the common maximum observations between geodetic stations [5]. Depending on the baseline lengths, the ambiguity resolution strategy was chosen. For short baselines, the SIGMA strategy was used. While, for long baselines, the Bernese quasi-ionosphere-free method was applied. The processing flow chart is shown in Figure 4. Table 2 shows the obtained reference final coordinates from a combined solution of the daily processing.

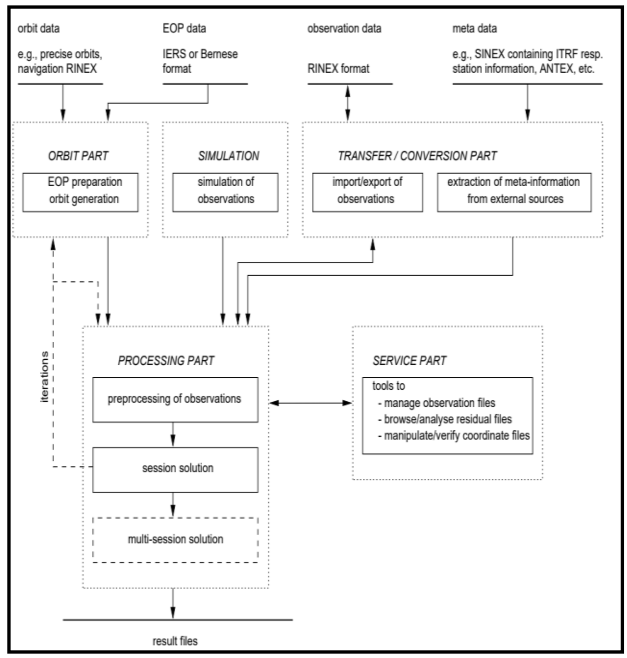

Figure 4: Bernese v5.2 processing flow chart [4].

Table 2. Reference Final coordinates solution.

Station	Lat.	Long.	Height
BORG	29.57370225	30.86335912	98.071
KATA	31.82921882	29.9274943	495.55
HURG	33.83229915	27.24443274	37.353

Table 3. RMS and reputability values for each EPGN station.

Station	Repeatability in mm			RMS values in mm		
	X	Y	Z	X	Y	Z
BORG	2	3	4.5	0.1	0.2	0.4
KATA	2	2	5	0.3	0.1	0.2
HURG	3	1	3.5	0.2	0.4	0.5

5. RESULTS AND DISCUSSION

Figure 5 shows the chosen earthquakes and the nearest GNSS stations. The subduction zone of African and Eurasian plates causes continuous large earthquake events. So, our first chosen earthquake happened on 2-05-2020 (Day of Year (DOY) 123) at the subduction zone of the Hellenic arc in Greece with a magnitude of 6.5. The nearest GNSS was BORG station. The distance between the epicenter and the GNSS station is 620 km. In Figure 6, the time series for horizontal displacements associated with the first earthquake is demonstrated. It is found that there is a signal of deformation that can be clarified from horizontal displacements before the earthquake (see Figure 6, red circle). On the other hand, after the earthquake, the deformation tends to be stable. Because of the energy from the earthquake. While in vertical displacement (figure 7), there is a disturbance in vertical deformation before and after the earthquakes. The vertical displacement reaches 2 cm. Despite the long distance between the earthquake epicenter and the BORG station, the deformation is noticeable in BORG.

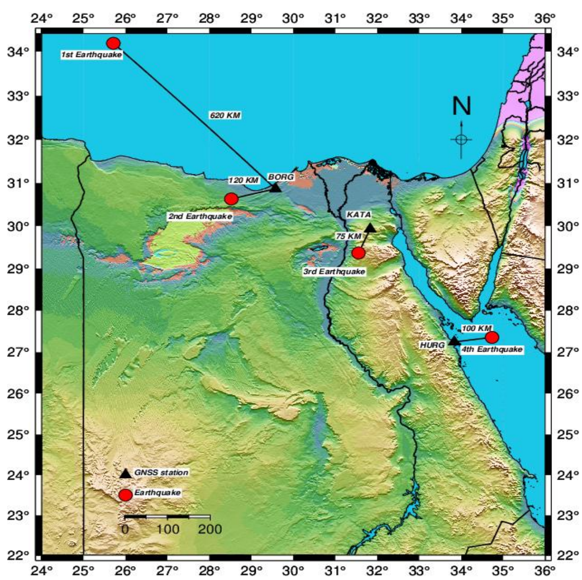

Figure 5: The chosen earthquakes and nearest GNSS stations from EPGN.

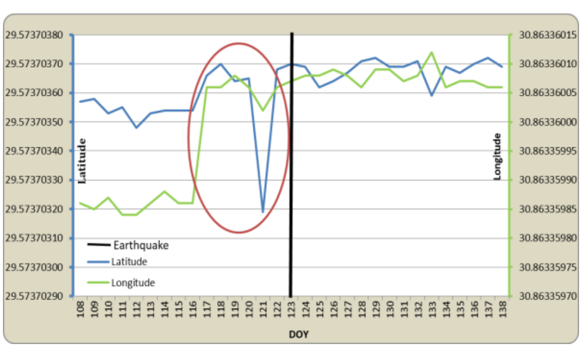

Figure 6: Horizontal displacement of BORG station with an earthquake of 02-05-2020

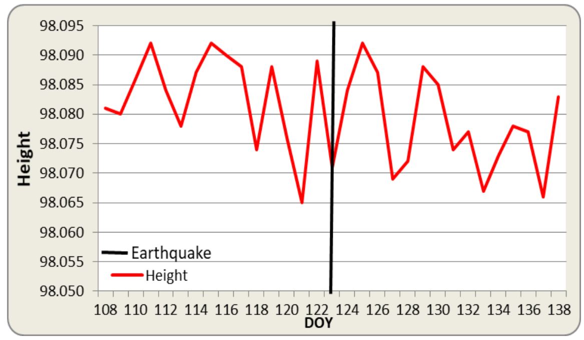

Figure 7: Vertical displacement of BORG station with earthquake of 02-05-2020.

The second tested earthquake was near Al-Alamayn, Egypt with a magnitude of 4.5 and depth of 47 km. This earthquake took place on 02-09-2015 (DOY 245). With distance between the epicenter and BORG station of about 120 km. It is noticed from Figure 8 that the horizontal displacements show a signal of jumping before the earthquake in both latitude and longitude values. Moreover, the vertical deformation (Figure 9) shows the same behavior of jumping in its values before the earthquake. After the earthquake the earth's deformation is low and there is no jump or considerable signal.

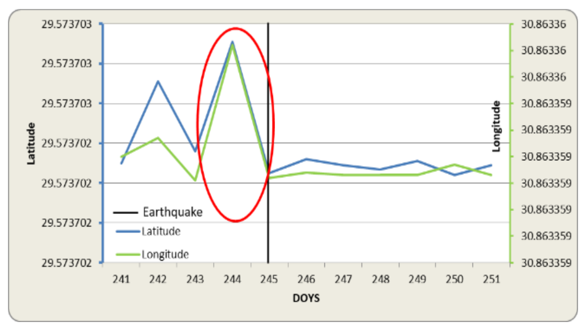

Figure 8: Horizontal displacement of BORG station with earthquake of 02-09-2015.

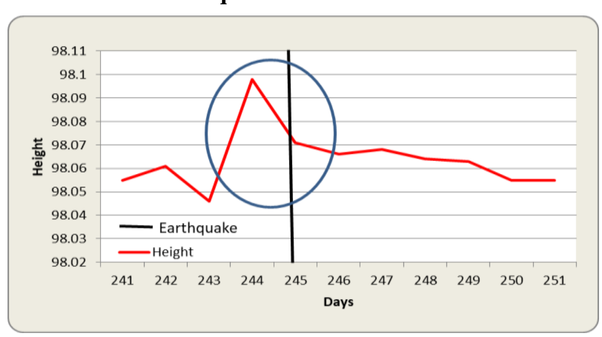

Figure 9: Vertical displacement of BORG station with earthquake of 02-09-2015.

The third example of displacement variations with earthquake activity was studied. In this example, an earthquake took place near KATA station. This earthquake happened on 01-02-2022 (DOY 32) with a magnitude of 4.3 and a depth of 10 km. The distance between the epicenter and KATA station is 75 km. When we take a look at the horizontal and vertical displacements (Figure 10, 11) before and after this earthquake we cannot distinguish a certain behavior of displacement before or after the earthquake. This may be because displacement associated with earthquakes is affected by many factors such as Earthquake magnitude, depth of the earthquake, the distance between the epicenter and GNSS station, and type of rock from the epicenter and GNSS station. The type of rock may cause amplification of the earthquake signal such as case of sedimentary rock. In addition, hard rock gives low amplification values.

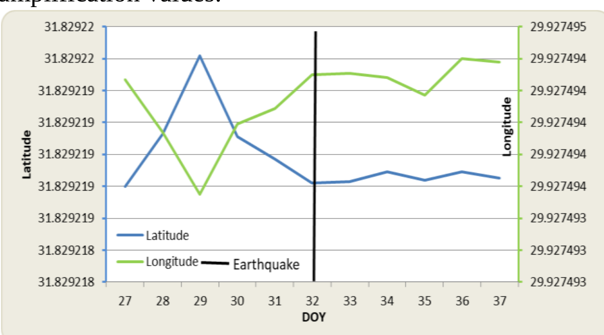

Figure 10: Horizontal displacement of KATA station with earthquake of 01-02-2022.

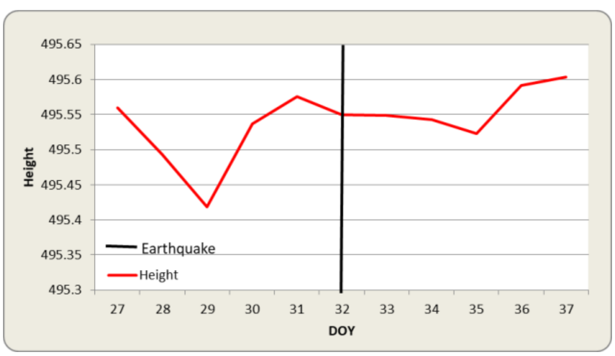

Figure 11: Vertical displacement of KATA station with earthquake of 01-02-2022.

The last tested earthquake was found in the Red Sea near HURG station. The magnitude of the earthquake equals 5.5 with a depth of 77 km. The date of the earthquake is 16-06-2020 (DOY 168) with a distance of 100 km from HURG station. As in the third example, the deformation related to the last earthquake cannot be identified. The horizontal and vertical displacements (Figure 12, 13) show irregular changes. The basement rock along the western bank of the Red Sea may play a role in reducing the effect of earthquakes happening in the middle of the Sea. So, a signal of change in position can be detected from GNSS observations before and after the earthquake activities. But, in some cases, we cannot detect this signal because the other factors control the seismic activities masking the position signal.

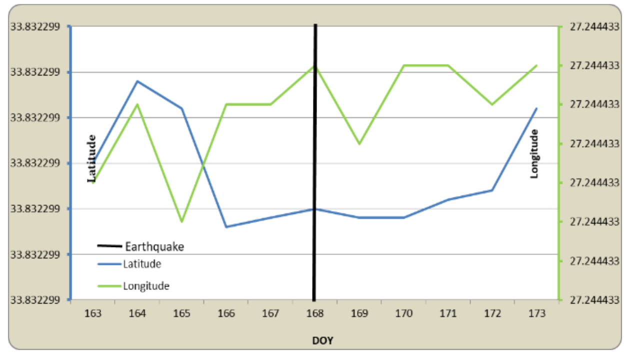

Figure 12: Horizontal displacement of HURG station with earthquake of 16-06-2020.

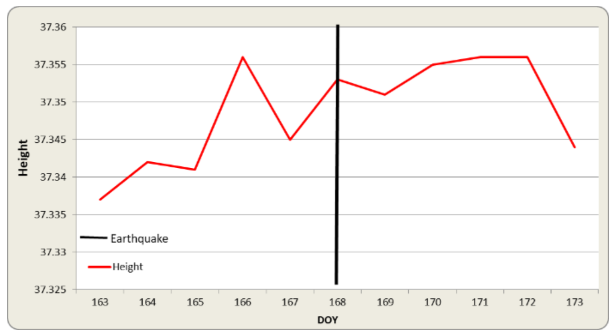

Figure 13: The vertical displacement of the HURG station with an earthquake of 16-06-2020.

6. SUMMARY AND CONCLUSION

In the current study, the evaluation of GNSS as a tool for detecting displacements accompanying earthquake activities was examined. In Egypt, Because of the subduction process between Africa and Europe, deeper activity is mainly concentrated along the Cyprian and Hellenic Arcs, while shallow activity is mainly concentrated in the vicinity of plate boundaries and on some active seismic zones like the Aswan, Abu Dabbab, and Cairo-Suez regions. We can see that most of the earthquake activities in Egypt are shallow type. GNSS represents an accurate technique for calculating positions. By using GNSS observations, displacements before and after the earthquake activities can be observed. In our study, GNSS observations from the EPGN network have been used for studying deformation during earthquake activities. A signal of deformation can be measured before the earthquakes of 02-09-2015 and 02-05-2020 at BORG GNSS station. While, for an earthquake of 01-02-2022, there is no clear signal can be observed. This may be due to the long distance between the earthquake epicenter and the GNSS station

We can conclude that GNSS observations can be used as an early warning system for earthquake prediction. So, it is recommended to establish GNSS stations side by side with any seismometer. Also, in

Egypt, there is a need for real-time GNSS observations to make an early warning GNSS system. In addition, GNSS stations in Egypt do have not good distribution because of the lack of stations in many areas in the eastern and western deserts. So, GNSS stations have to add to EPGN to cover all of Egypt.

7. DECLARATION

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Credit Authorship Contribution Statement

The authors confirm their contribution to the paper as follows:

Author1: Analysis and interpretation of results, Draft manuscript preparation.

Author2: Study conception and design, Data collection, Analysis and interpretation of results, Draft manuscript preparation, reviewed the results and approved the final version of the manuscript.

Author3: Analysis and interpretation of results, Draft manuscript preparation.

Author4: Reviewed the results and approved the final version of the manuscript.

Declaration of Interest Statement

The authors state that they have no known conflicts of interest or close personal ties that could have influenced the research reported in this paper or be perceived to have influenced it.

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