



# Utilisation of GNSS and seismicity for monitoring crustal deformation of the Northern part of the Nile Delta, Egypt

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## ABSTRACT

Nile Delta is one of the most significant regions in Egypt. The offshore Nile Delta is located in a complex structural area of Mediterranean Ridge, which is an important wrench fault separating the Arabian plate to the African Plate. This study aims at monitoring the recent crustal deformation and velocity of the Northern delta beside its connection to the seismicity and tectonic activities of the African plate using the permanent GNSS stations distributed at the Egyptian Delta and Europe. The available GNSS data (2009–2019) were analysed utilising the Bernese 5.2 software, to identify the velocity vectors, and the principal segments of crustal strains along the investigated region. The results show that the average absolute velocity ranges between 14 and 22 mm/yr with an accuracy of 3 mm/yr, and the residual velocity is estimated at 0.51 to 4.98 mm/yr with an accuracy of 2.5 mm/yr. Furthermore, the rate of the gathered strains in the northern Nile Delta was recently changed from low to moderate. The outcomes show that the area under investigation suffers from irregular seismic activity related to the crustal movements, which occurred along with the major fault trends in the region.

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## 1. Introduction

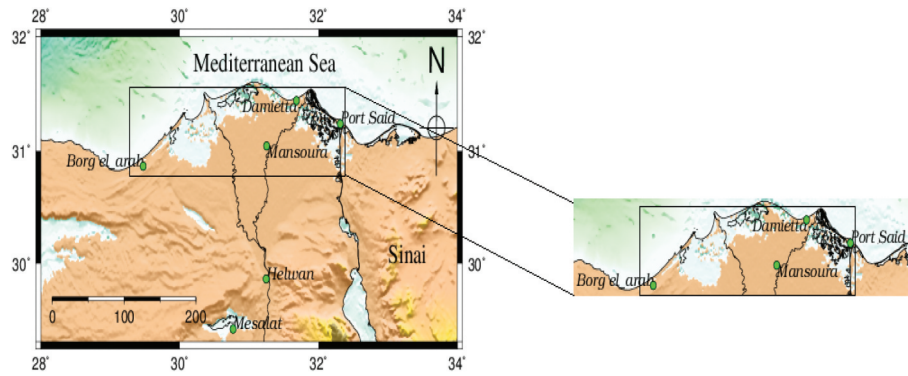
Monitoring recent crustal deformation of the Egyptian Nile Delta is crucial for its strategic significance. Therefore, several studies investigated the crustal deformations of the Nile Delta. Among these studies is Saleh (2011), which measured the average displacement of the horizontal movements in the Nile Delta. Another study by Mahmoud (2003), and Badawy (2005) aims to study seismicity and deformation in Egypt. The present study employed the available GNSS data (2009–2019), which was acquired based on two sources; 1) The permanent Egyptian stations (seven stations) that covering study area and distributed in the Northern part of Nile delta and around these areas, and 2) some permanent international stations (IGS) in Africa and Europe. These accumulated data have been used to determine the direction of the horizontal and vertical movements beside the absolute and relative velocities. The key objective of this study is to estimate the strain tensor parameters such as the maximum shear strain rate, the dilatation rate, and the principal strain parameters. The seismic data are gathered from the Egyptian National Seismic Network (ENSN) and other sources. The final aggregated output from the seismic and GNSS data focuses on the area's geodynamic system and its endeavour to delineate the crustal stress and strain fields.

### 1.1. Study area

The Nile Delta is one of the world's largest river deltas, where it extends from Alexandria in the west to Port Said in the east. It covers about 240 km along the Mediterranean coastline and is mainly composed of fertile agricultural lands. It is, therefore, the home of almost half of the Egyptian population; it is considered one of the world's highest density regions with more than 1,000 habitants per square kilometre. This study deals with the northern part of the Delta, which contains the largest city in the Delta, due to its significance in the current vision of development planning of the northern coast of Egypt (Figure 1).

### 1.2. Geological and tectonic settings

The modern Nile Delta is positioned south of the Nile Cone, a depositional feature resulting from quite Five million years of discharge and deposition of 3500 m of sediment by the Nile and Paleo-Nile drainage systems (Sestini 1989). The Pleistocene section consists of up to 800 m of deltaic sands with minor clay layers (Research Institute for Groundwater (RIGWA 1992)). During the Pleistocene, from roughly 18 to 35 km, the contemporary Nile Delta was a seasonally active alluvial direct with braided flow channels. The Delta prograded up to 10 m/yr into



**Figure 1.** Geographic extension of the study area.

the Mediterranean through the accretion of silts and clays (1–7 mm/yr), giving rise to thicknesses of up to 60 m of Holocene deltaic fluvial/marine deposits (Stanley and Warne 1994). Throughout the Holocene, centres of deposition continued to shift from one spot to a special along the delta coastline, counting which channel(s) were active at any particular time (Stanley et al. 2004). The Nile delta subdivided into two sub-provinces by a faulted hinge line-oriented WNW to ESW located at Kafr El Sheikh Latitude city. This hinge line is illustrated because the faulted flexure separates the southward delta province from the northward Delta plain basin. The E-NE and NE trending folds on lately Cretaceous to Eocene age (the Syrian arc folds). The hinge line is a faulted flexure zone (30–40 km width) that affected the Pre-Miocene formations and extends from E–W across the Mid Delta area (Said 1981). The Oligocene to Early Miocene NW-SE trending faults were related to a huge uplift including basaltic extrusion. The studies of the overpressured sediments in the offshore Nile Delta illustrated that pore pressures are largely related to under compaction (Badri et al. 2000). The Tertiary rocks are thin and sandy compared to the thicker and more shale-rich equivalent rocks in the more distal in the offshore areas of the Nile Delta (Nashaat 1998).

Tectonically, the study area occupies a key position within the context of the plate-tectonic evaluation of the eastern Mediterranean Sea and the northern part of the Red Sea (Figure 2). It lies on the moderately deferent external margin of the African plate (the Unstable Shelf, Said 1962), extending along the northern coast of the Mediterranean Sea. The Nile Delta is often subdivided into four subsequent structural sedimentary provinces (Sarhan and Hemdan 1994) as follows (A) The South Delta province, a continuation of Western Desert stratigraphic sequences and structure. (B) The North Delta basin. (C) The Nile Cone. (D) The Levant platform. The primary tectonic phase is that the Neotethys rifting formed the North Africa development of a thorough system of generally E–W trending rift basins located inboard from the

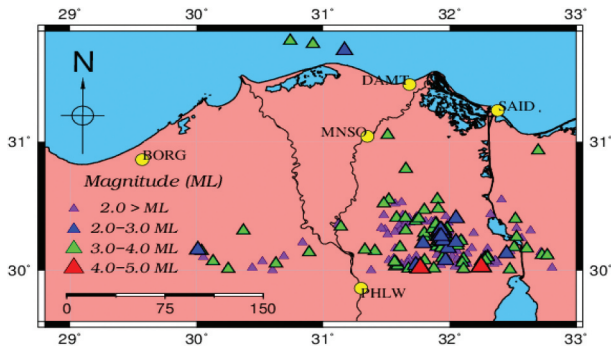


**Figure 2.** Simplified map of the Arabian plate, with plate boundaries, approximate plate convergence vectors and principal geologic features (Stern and Johnson 2010).

continental margin. The second phase is manifested by the NW–SE (WNW–ESE) – oriented normal faults. This is part of the most significant tectonic event that affected the northern part of Egypt, during the late Cretaceous and Early Tertiary periods. It is characterised by major and minor faulting originating by compressive forces along a period of movements followed by a fast action period of tensional relief (Said 1990).

### 1.3. Seismicity and focal mechanisms solutions

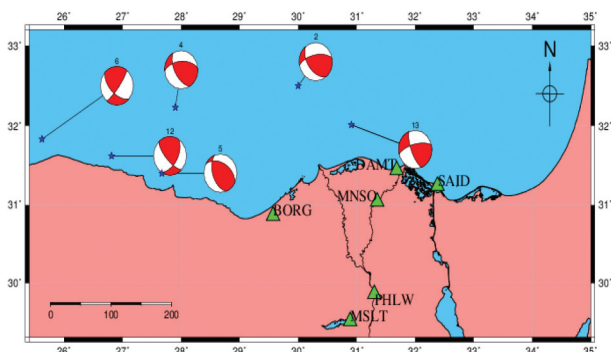
The documented historical earthquakes demonstrated that northern of the Red Sea, southern Gulf of the Suez and Gulf of Aqaba are the most active areas in Egypt (Badawy 1999). Seismic activities were recently recorded southwest and southeast of Cairo, the zone between Cairo-Ismailia and Cairo-Suez roads, along the Red Sea ocean coast and south Aswan (Abuo EL-Ela and Abou Elenean 2012). The connection of the African, Arabian, Eurasian plates and Sinai sub-plate is the main factor of the seismicity at the northern part of Egypt. There is no noteworthy seismic tremor at the Nile Delta zone, while the overwhelming majority of the varied earthquakes have occurred at the crossing point between the Mediterranean and Red Seas fault trends (Figure 3). Earthquake source mechanisms are



**Figure 3.** Seismicity recorded by Egyptian National Seismic Network (ENSN) from 2009 to 2019 around the Nile Delta region.

of prime significance in monitoring local, regional, and worldwide seismicity. Fault plane solutions in this study show a dominant compressional stress represented by a thrust faulting mechanism along ENE–WSW trend and normal faulting mechanism along NNW trend. However, a low number of focal mechanisms inverted for stress limit the reliability of the inversion and the results should be viewed as indicative only (Ali and Badreldin 2019).

They reflect the strain pattern acting within the zone under investigation and can contribute to mapping its tectonic structure, which causes a seismic tremor. Most of the investigations can practically utilise the direction of the foremost p-wave within the earthquake focal mechanism ponders during the era of 2009–2019, where several significant earthquakes occurred in Egypt (Figure 4). The east boundary of the northern African plate is characterised by the divergence accompanying the extension while the northern boundary is characterised by convergence accompanying the compression. The high level of seismic activity in Cairo–Suez districts interpreted to result in the interaction between these plates. The data utilised during this study include the earthquake catalogues and GNSS data. The earthquake data were



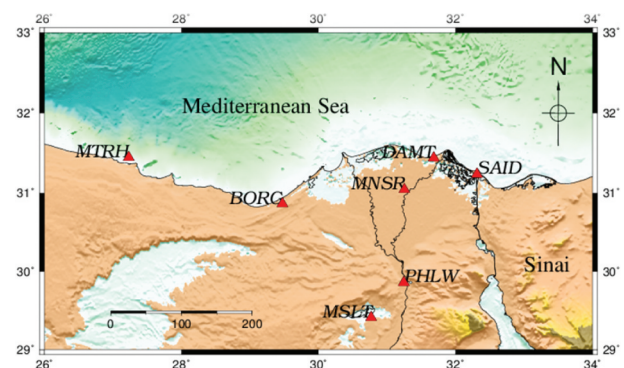
**Figure 4.** Epicentres and focal mechanisms of earthquakes in the Northern Egyptian Continental Margin region above GNSS permanent stations during the period from 2009 to 2017, Thrusting solutions (in red colour), and permanent stations (in green colour) modified after (Ali and Badreldin 2019).

collected from the Egyptian National Seismic Network (ENSN) from 2009 to 2019 (Figure 3).

## 2. Data and methodology

Seven stations from the Egyptian Permanent GPS Network (EPGN) were utilised in and around the northern part of the Nile Delta (Figure 5). These stations are Borg Elarab, Damietta, Port Said, Mansoura, Mersa Matrooh, Helwan, and Mesalat. They were picked to cover most of the investigation area with GNSS data range from 2009 to 2019. The time of the observed session is 24 hours, with a sampling interval of 1°. The GNSS data were processed using the freely available Bernese software V.5.2 (Dach et al. 2007), which fixed on the workstation of the National Research Institute of Astronomy and Geophysics (NRIAG). The data were processed to integrate some selected collection of the International Service (IGS) and permanent local station of the study area. The antenna at all sessions of measurements was focused over the marker and directed towards the North. The height from the upper surface of the antenna to the benchmark was fixed for all stations.

The adopted procedures for processing the GNSS data are 1. ITRF2008 reference frame, 2. NNR-NUVEL-1A plate motion model for non-ITRF stations, 3. Usage of the reprocessed CODE products up to the end of 2010 and the final IGS products for the remaining period (2009 to 2019), 4. Automatic baseline creation using MAX-OBS methodology, 5. Ionosphere free linear combination LIF, 6. Elevation cut-off angle of 5°, and 7. Dry Niell as a troposphere model with GMF (Global Mapping function) as a mapping function (Saleh and El-Dabaa 2018). During this work, the reprocessed items from the Centre for Orbit Determination in Europe (CODE) in Bern were utilised due to the absence of IGS reprocessed products that are perfect with ITRF2008 during the period 2009–2019. The handling methodology was carried out through the



**Figure 5.** Geographic distribution of GNSS stations in the Nile delta and along the delta shore line.



double-differenced observations system, by utilising this strategy, where daily minimum constrained solutions were acquired.

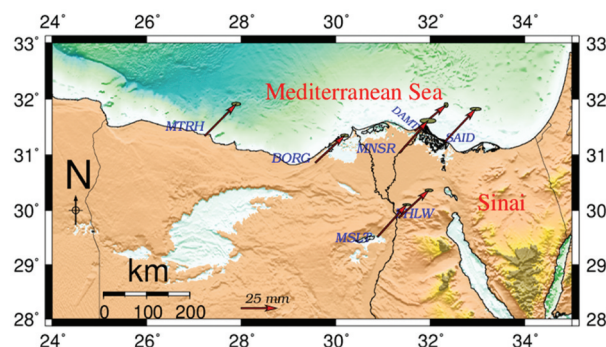
The strain analysis can be calculated by different methods based on three factors: (a) the available data set or observables, (b) the adopted geodetic method, and (c) the data processing strategy (Pietrantonio and Riguzzi 2004). The data processing strategy can be performed using one of the three techniques: (I) segmentation, (II) inversion, and (III) interpolation. The segmentation method was adopted to estimate the local strain by dividing the study area into several triangles, polygons (Blocks), and then the strain tensors were calculated over each block from the recorder displacements at the stations. This method is more suitable for estimating the strain rate over small areas with a limited number of measuring points. Accordingly, the strain can be calculated for each geometrical unit, as formulated by Jaeger (1996).

### 3. Results and discussion

The achieved results can be described in the following sections:

#### 3.1. Estimation of the velocity field

The investigation of the recent consequences of the absolute horizontal velocity field for the processed stations has revealed critical changes through the time of observation. The magnitudes of the absolute horizontal movements are distributed homogeneously. The maximum observed displacement during the time of study was determined in BORG, DAMT, MNSO, SAID, MTRH, PHLW and MSLT stations with magnitude 20.5, 21.8, 21.62, 20.55, 14.2, 21.07 and 20.05 mm/yr, respectively, in the East direction and with magnitude 18.9, 17.9, 22.63, 22.47, 22.23, 19.16 and 22.33 mm/yr, respectively, in the North direction, this can be alluded to the way that expanding the crustal movement along the margin of the plates. The northeast movements are still the dominant horizontal movement for all recorded stations with magnitudes between 17.9 and 22.63 mm/yr, in the northern segment and from 14.2 to 21.8 mm/yr, in the eastern part, as it appeared in Figure 6. The



**Figure 6.** The horizontal velocity of the Northern part of Nile delta Network region (including the.

horizontal movement of the permanent stations of the northern part of Egypt (Borg-Elarab, Dameitta, Port Said and Mansoura) can be identified with the Nile delta Subsidence. The horizontal movement of the investigated stations is considered a part of the horizontal movement of the African Plate and the stations' velocities, including the African Plate movement.

The estimated relative velocity field is expected to provide a better understanding of the geodynamical situation of the investigated territory and constrains of the ground deformation of the Northern part of Nile delta. The relative movement of one plate regarding another plate can be depicted by a relative kinematic plate model or rotation angle ( $\Omega$ ) around a point on Earth's surface or Euler pole. Various distinctive Euler poles parameters have been proposed by different authors to portray the relative motion of the African Plate (Ex. Saleh 2015). It is well known that the stations of the northern part of Nile Delta network show significant changes more than the southern parts, for instance, Borg El-Arab, Damietta and Port Said stations in the northern parts, Mansoura in the Middle section, while Helwan and Mesalat as a reference station. These stations demonstrate insignificant changes, which could be the principal reason for this region's seismic activity. The movement in a different direction of some stations of the northern Nile Delta can be attributed to the extensional system which overwhelmed this region. This local deformation could be referring to the dominant domal structure in the investigated area. The results of the annual

**Table 1.** Geodetic stations and annual horizontal velocity of the Northern part of Nile delta region including the velocity of the African plate.

Station Name	Station ID	Long(E)	Lat. (N)	V. E (mm/yr)	V.N (mm/yr)	( $\sigma$ ).E (mm)	( $\sigma$ ).N (mm)
Borg El-Arab	BORG	29.5737015	30.8633576	20.55	18.9	1.15	0.45
Damietta	DAMT	31.6831463	31.4397367	21.8	17.86	0.58	0.71
Mansoura	MNSO	31.3526040	31.0410263	20.05	22.33	2.30	0.68
Mesalat	MSLT	30.8887073	29.5138204	20.55	22.47	1.16	0.27
Mersa Matrouh	MTRH	27.2305345	31.3457296	14.19	22.23	1.28	0.52
Helwan	PHLW	31.3433989	29.8615467	21.07	19.16	1.12	0.37
Port Said	SAID	32.3143384	31.2456945	21.62	22.63	1.57	0.45

horizontal velocity of the northern Nile Delta and the African Plate are explained in Table 1 and Figure 6. By extracting the values of the annual horizontal velocity of this region including the annual horizontal velocity of the African plate, which can be used to calculate the annual horizontal velocity of the Northern part of Nile Delta geodetic network region as shown in Table 2 and Figure 7). In tectonic and geodynamic studies, the strain rate tensor is significant, because the tensor analysis can detect different aspects of deformation such as uplift or subsidence. Additionally, the accumulation of the fault strain either shear or dilatation strain rate, including its direction, represent the key parameters for seismic hazard assessment (Goudarzi et al. 2014).

Velocity of the African plate).

### 3.2. Results of strain analysis

The study area is divided into three blocks, block no. 1 includes stations of Port Said, Helwan, Mansoura and Damietta (SAID, PHLW, MNSO, and DAMT), the block no. 2 includes the stations of Meslat, Helwan, Borg El Arab, and Mansoura (MSLT, PHLW, BORG, and MNSO) Block 3 includes the stations Damietta, Mansoura, and Borg el Arab (DAMT, MNSO, and BORG). Table 3 shows the strain parameters for all blocks including the calculated parameters of the maximum principal strain rate (E1), minimum principal strain rate (E2), the direction of the maximum principal strain rate ( $\alpha$ ), maximum shear strain ( $\gamma$  max) and the dilatation ( $\Delta$ ) (Fuji 1997).

The dilatation strains for the study area are shown in Figure 8, where the extension force is dominated in

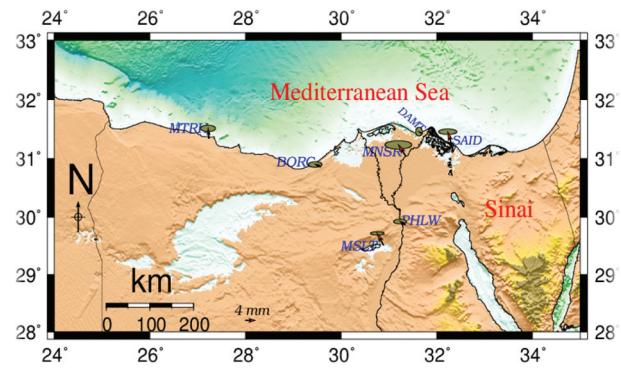


Figure 7. The residual annual horizontal velocity of the northern part of Nile Delta region.

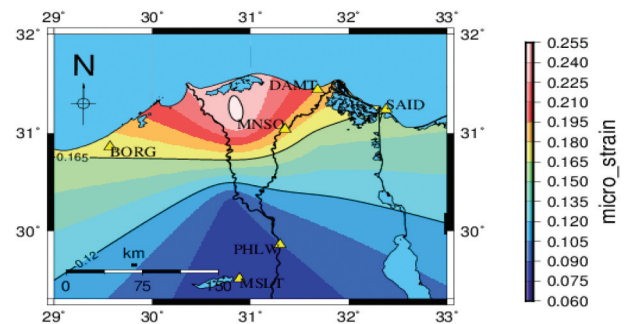


Figure 8. Shows the dilatation strains selective Egyptian Permanent Stations for the study area.

the northern part of the study area with positive values of dilatation ranging from 0.255 to 0.165  $\mu$ s. The compression force is dominant in the southern part with negative dilatation values ranging from 0.06 to 0.150  $\mu$ s. In conclusion, the study area is located between two zones of dilatation (compression force) and (extension force) separated by the seismic zone.

Table 2. Geodetic stations and residual horizontal velocity of the Northern part of Nile delta region.

Station Name	Station ID	Long(E)	Lat. (N)	V. E (mm/yr)	V.N (mm/yr)	( $\sigma$ ).E (mm)	( $\sigma$ ).N (mm)
Borg El-Arab	BORG	29.574	30.863	-2.3485	0.9087	0.00115	0.00045
Damietta	DAMT	32.314	31.246	-1.1015	0.5138	0.00058	0.00071
Mansoura	MNSO	31.353	31.041	-3.1168	4.5581	0.0023	0.00068
Mesalat	MSLT	30.889	29.514	-2.6806	4.6392	0.00116	0.00027
Mersa Matrouh	MTRH	27.231	31.346	-8.2734	3.9762	0.00128	0.00052
Helwan	PHLW	31.343	29.862	-2.2008	1.3868	0.00112	0.00037
Port Said	SAID	32.314	31.246	-1.6815	4.9838	0.00157	0.00045

Table 3. Strain parameters of the northern part of Nile Delta geodetic network region.

Block No.		Principal strains			Shear ( $\gamma$ max)	Dilatation ( $\Delta$ )
		E1	E2	Direction ( $\alpha$ )		
I	Port Said (SAID)	1.517E-05	2.154E-05	130.9997	-6.365E-06	3.671E-05
	Helwan (PHLW)					
	Mansoura (MNSO)					
	Damietta (DAMT)					
II	Mansoura (MNSO)	3.305E-06	-2.994E-05	16.0523	-2.663E-05	3.324E-05
	Helwan (PHLW)					
	Mesalat (MSLT)					
	Borg El-Arab (BORG)					
III	Damietta (DAMT)	1.312E-04	-1.556E-06	-82.3030	1.296E-04	1.328E-04
	Mansoura (MNSO)					
	Borg El-Arab (BORG)					

The results indicate that the total of maximum shear strain accumulation during the same interval is relatively small and lies in the lowest class and covers most parts of the region (Fuji's classifications, 1995). Furthermore, the medial shear strain part covers a few parts of the area. The shear strain for the study area from 2009 to 2019 is shown in Figure 9. Most parts of the study area are characterised by medium values of shear strain ranging from 0.25 to 0.165  $\mu$ s and concentrated in the eastern and middle parts. In contrast, high shear strain areas do not necessarily correspond to high seismic hazards because the major parts of deformation are not accumulated as elastic energy (Malservisi et al. 2005).

The distribution of the principal strain axes through the period (2009–2019) is illustrated in Figure 10. Most of the compression and extension forces are limited where the rate of extension force increases in the North and East part. The compression force is concentrated in the North and middle parts with Northeast- Southwest. Table 3 shows the three blocks with the strain rate parameters for each block.

### 3.3. Results of time series estimation

The time series for the selected GNSS pixels from the investigated stations is designed to compute the displacement rate for each station. In general, different information can be extracted from the geodetic time series; it can also provide the stability of each station. Each station's displacement and direction with the expected time for

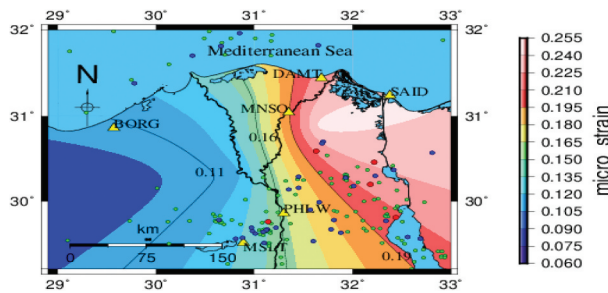


Figure 9. Distribution of the maximum shear strain rates at the Nile delta and around area.

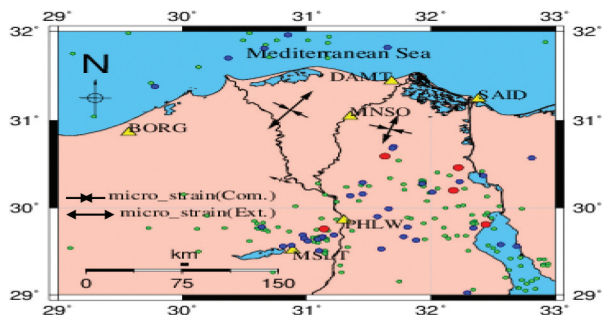


Figure 10. Principle strain for permanent stations of study area.

the activity were utilised to extract the GNSS observations seasonal effects. The geodetic time series were generated for the study area from the processing of the GNSS data of the Five Permanent Stations during the period from 2013 to 2019 (Figure 11). Each small solid signal on the plot in (Figure 11) represents an independent position estimate typically, with error bars. The black lines represent the linear horizontal velocity, while the dots represent each campaign's solution. The deformation analyses results can be noticed at most of the deformed stations in all epochs are large in the East direction than in the North direction. The magnitudes of the deformed stations are variable from one station to another and inhomogeneous over the area. The orientations of the pressure and tension stresses in the North Delta region are ESE-WNW and NNE-SSW, respectively.

### 3.4. Discussion

The crustal deformation and Seismicity within the Northern Nile Delta were acquired from both the GNSS and Earthquake data. The outcomes from these data collections are consolidated recognise the foremost characteristics of deformation and hazard assessed. The GNSS and seismological data analysis output highlights the geodynamical system of the seismic activity and puts the Northern Nile Delta region under the minimum class as per level horizontal crustal strain arrangements. According to the strain tensor analysis, the southeastern part of the study area is described by compressional forces, and thus the northern part has experienced expansion forces. The outcomes show that the region suffers from low to medium seismic activity identified with the crustal movements that occurred along with trends of major faults in the study area. Furthermore, the consistent urban expansion and the excessive extraction of groundwater may influence the strain system in the northeastern part of the Nile Delta, and that could be a source for seismic activity. The final output from the seismological and geodetic investigation focuses on the territory's geodynamical system as an attempt to monitoring the crustal stress and strain fields. In terms of estimating the essential rule, the surface strain rate tensors partially concur with earthquake occurrence.

## 4. Conclusions

The objective of this study is to scale back a risk of giant disastrous losses inside the varied zones, particularly the Nile Delta of Egypt. The study outcomes can be summarised in the following points:

- The magnitudes of the horizontal and vertical displacement are varying between 3 and 5 mm/year. It is obvious from the magnitudes of the movements in conjunction with the deformation



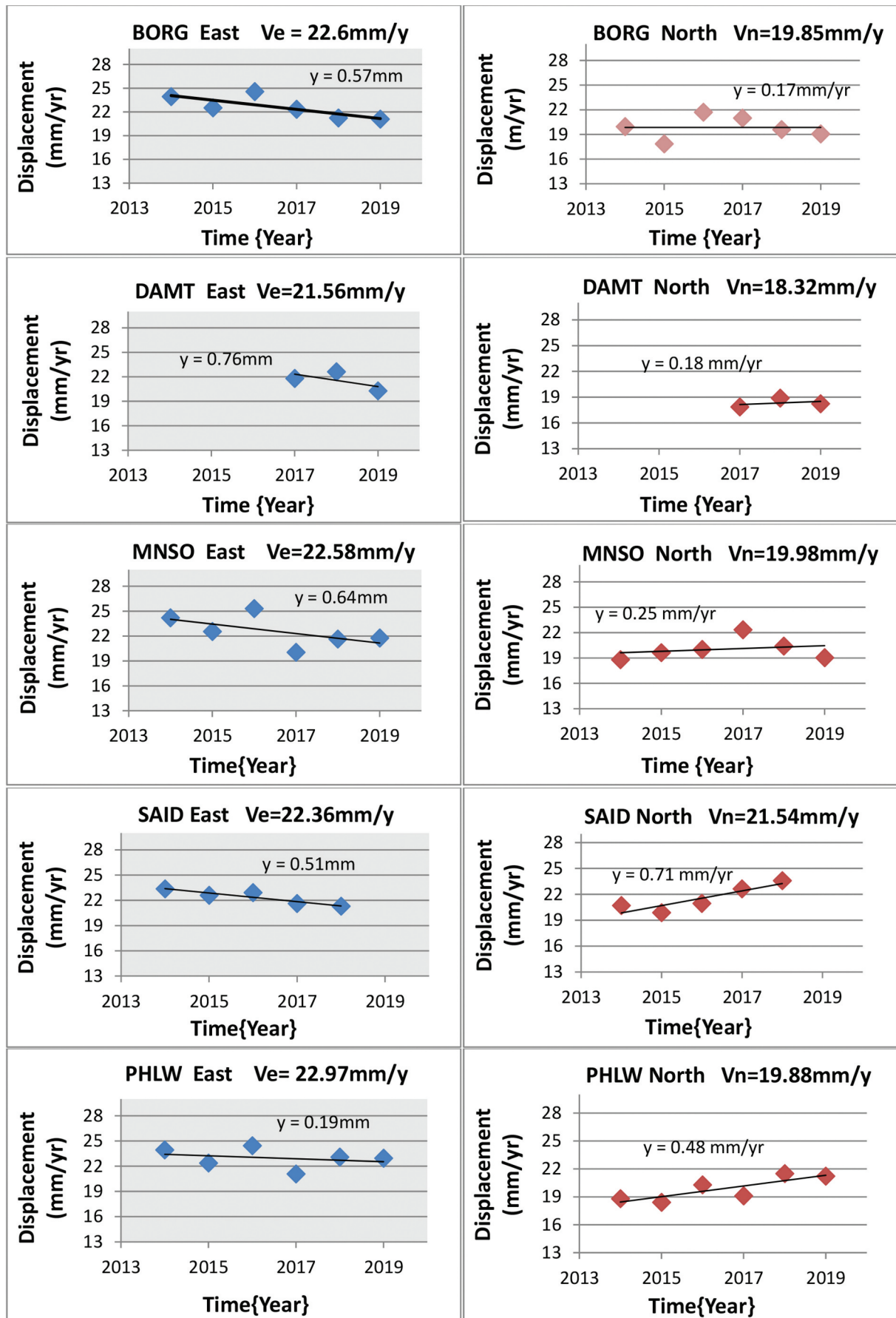


Figure 11. Shows the time series graphs in north, east direction of permanent stations at study area.

fields that the northeastern part has suffered from variable extension. The southern and middle

parts of the study area have experienced compression from one epoch.

- The rate of the gathered strains is low and lies within the minimum class of the category of the strain classifications. This demonstrates the stability of the investigated region.
- The seismic hazard was employed to depict the likelihood of earthquakes with the dimensions kind of a selected value within a specified region and a given time span. The blending between seismicity and GNSS makes it hard to gauge where subsequent damaging quake in this region may happen.
- Absolutely, the best seismicity rates are found at the eastern boundaries of Egypt, and thus the littlest amount rates are found at the Northern Nile Delta and the surrounding areas.
- The focal mechanism of some earthquake events recorded during the studied period is very low and show mainly normal and strike-slip faulting.
- Horizontal velocities in the study area are small except in Mansoura and Port Said stations are medium.
- Distribution of the dilatation in the study area indicates that the southern and middle parts are suffered from compression force, especially in the Mansoura area, however, the northern part suffered from extension force.
- Distribution of the shear reflects that most values are found in Mansoura, Damit and Port Said stations. This triangle area is characterised by a low seismicity and its shear value decreases towards the west.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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