Assessment of Crustal Deformation in Earthquake Process

ABSTRACT

Crustal deformation involving displacements of Earth mass is an essential variable used in observing and modelling seismic activities. It can be observed by using various approaches especially the geodetic techniques to undertake measurement at a predetermined level of repetitions on the Earth. The utilization of geodetic systems has significantly enhanced the manner by which crustal movement is being monitored and managed. An obvious indication of this is the reasonable level of accuracy, and the substantial spatiotemporal coverage practicable when space-based methods are used. The broad aim of the current study is to review existing literature relatively to the assessment of crustal deformation. First, an overview on crustal deformation is presented. This is followed by a review on instrumentation and techniques for crustal deformation assessment including Global Navigation Satellite Systems, remote sensing, and gravimetry. Finally, this review shows that geodesy in general and particularly space-enhanced techniques are characterized by improved capacity for detecting and monitoring crustal movements and deformation.

Keywords: Deformation, earthquake, fault, InSAR, seismic, tectonics

1. INTRODUCTION

The Earth's crust is subjected to both internal and external influences, which are dominated by the gravitational force, and consequently, its surface is in a constant modification. For instance, the atmospheric and hydrological components can cause distortion of the Earth's crust because they influence the Earth's gravity in line with Newton's gravitational law. This, along with the associated loading consequences on the earth's exterior distorts the lithosphere [1].

Surface movements comprise different plate distortions, distortions of Earth crust or glacier ice flow, and many other phenomenon. Assessments involving active tectonics predominantly relate to Earth's surface distortions [2], which primarily results from the features of tectonic plates. The main assumption of plate tectonics is that the surface of the crust is separated into numerous plates, or into nearly rigid lithospheric plates that slide on each other, and the Earth's internal layer which cause crustal deformation especially at the plate boundaries [3,4]. In other words, plate tectonics is the theory that the Earth's lithosphere is divided into tectonic plates that move around on top of the asthenosphere. It explains how large pieces of the Earth's outermost layer, called tectonic plates move and change shape. Plate tectonics influences increase and discharge of strain through seismic activities [5]. For this reason, its effect is not only on the planetary interior, but also, on the surface and atmosphere. Thus, plate tectonics plays significant role in stabilizing the Earth's surface by means of stable lithospheric flow with regards to the Earth surface and deep Earth from the mantle transition zone. Of course, various studies indicate plate movements are responsible for many tectonic activities in the past and modern times including earthquakes, distribution of topography and heat flow in the oceans, etc. Combining poles of different ages in a particular plate to produce apparent polar motion paths provides a method for comparing the motions of different plates through time [6]. Though plate motion is used to explicate most of the surface features of the Earth, its cause is still not completely comprehensible. However, the main forces thought to be responsible for it include convection current, gravity, thermal plumes, and cosmic influences.

Various presumptions about the cause of tectonic plate motions attribute it to large scale convection currents in the upper mantle which are transmitted through the asthenosphere. Arthur Holmes and some other scientists propounded the theory in 1930s that thermal convection within the Earth's mantle provides the required force to drive continental motions. Also, Cande and Stegman [7] ascribed tectonic movement to mantle plumes by suggesting that they can exert a significant force on plates. According to their assumption, if a growing plume head impinges on the base of a tectonic plate long after supercontinent breakup and distribution, then its pushing force may lead to an extensive acceleration or deceleration of plates. The appearance of big plumes under the lithosphere involves considerable thermal weakening of magma above the plume head [8]. Furthermore, many researchers suggest that gravitational sliding away from a spreading ocean ridges occur with plate motion due to the higher elevation of plates at ocean ridges [9].

Understanding the patterns and rates of crustal distortion determines the understanding of the dynamics in the lithosphere, and seismic phenomenon [10]. Thus, precise observational information of Earth's deformation is essential to identify spatiotemporal changes on the Earth. Mapping 3-dimensional Earth's surface deformation is now increasingly more important for the analysis of earthquakes and volcanic eruptions. But, quantifying the current deformation has been difficult due to lack of observational method for accurately measuring the broadly distributed and complex patterns of movement [11].

The conventional technique of plate tectonic modelling involves the inversion of global datasets, which are normally generated from the geologic records on the average information of plate motion for 3-5 years. Also, Earthquake Early Warning (EEW) systems employ properties of elastic waves recorded on inertial seismometers to measure the magnitude and epicenter of an earthquake [12]. However, the technique of space geodesy offers a better approach for deformation measurements [13] as it can be used to achieve reasonable level of accuracy based on geodetic observations from GPS, airborne radar Interferometry, and high-resolution observation.

Crustal Deformation

Crustal deformation can result from tectonic influence, volcanic activities, and anthropogenic conduct such as aquifer withdrawal or geothermal exploitation. It is the alteration of the Earth, which usually leads to earthquakes. Earthquake is an overwhelming and disastrous natural phenomenon, which exposes human beings to serious threats [13], as such; it has attracted many studies for several decades. Deformations of the crust resulting from plates' movement produces an extensive array of landforms on Earth, and their size depends on the duration as regards to the process of their formation.

Generally, there are four chronologically diverse stages in the course of seismic sequence within an active fault (see Figure 1, Reddy et al., [14]), including pre-seismic, inter-seismic, coseismic, and post-seismic phases. Pre-seismic (nucleation) period results to a number of incidences, probably affecting the lithosphere and the atmosphere. Inter-seismic stage exists for several years involving loading stage, whereby stress in the Earth crust steadily accumulates on the locked fault surface. Earthquakes normally take place as soon as the accumulation of strain within the time of inter-seismic activities produces stress that is stronger than the fault's friction [15]. Coseismic phase is a short period during which the accumulated strain is released during earthquakes. In other words, it comes with rapid volume surface strain. Studying coseismic stage is essential in order to comprehend the earthquake processes. The long-term accumulated flexible strain is usually recovered within the coseismic incidence leading to the translation of material at both sides of the fault [2]. Post-seismic stage is the period immediately after an earthquake, which exhibits relatively higher degrees of deformation in which the material deforms due to the abrupt coseismic release of strain. It exists for a number of decades, and at this stage, the stress alterations passed on by the earthquake produces crustal and lithospheric distortion that is drastically quicker than the inter-seismic rates. One significant feature of the post-seismic phase is the subduction zone deformation which is concerned with both short-terms after-slip on the fault plane and long-term visco-elastic relaxation of the lower crust/upper mantle [16-18].

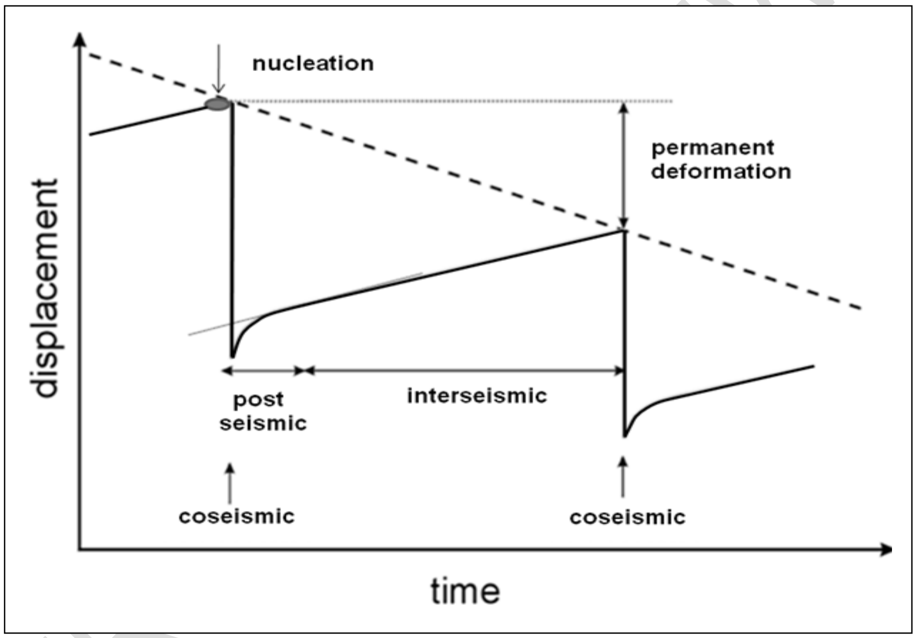

Figure 1: Idealized seismic cycle constituting four distinct phases.

Understanding plate tectonics' movement, plate boundary region and characterizing the probable sources of earthquake rupture is fundamental to achieving successful seismic risk estimation [5]. It is also important in deducing the correlation between the growth of geological formations and deformation in individual earthquakes. This can be achieved through measurement of earthquake displacement fields and modelling of fault slip. Now, more stable amount and precise crustal deformation measurements in diverse tectonic contexts subsist. The new data inspired the growth of geophysical models trying to portray the features of the cyclic behaviour of crustal stress build-up and release, originally suggested by Reid in his Elastic Rebound Principle [19]. The elastic rebound theory offers a coherent means of forecasting earthquakes. It states that a large earthquake cannot occur until the strain/stress along a fault exceeds the forces holding the rock masses together [19]. Tectonic geodesy has facilitated the growth of models that depict the development of slip throughout the earthquake sequence [20]. It is possible to deduce the fault's geometric characteristics, the spread of slip and to compute the related moment discharge by using elastic displacement principle.

2. METHODS OF CRUSTAL DEFORMATION ASSESSMENT

The purpose of investigating and monitoring crustal deformation is to identify and understand slight transformations in the Earth's geometry, which is connected to seismic movement along faults. In this regard, geodesy application is of immense significance. Geodesy deals with measurements to establish precise location on the Earth, and the variations of Earth gravity and magnetic fields. It involves the repetitive acquisition of geometric and gravimetric data with the highest level of precision and resolution. Geodesy is thus able to determine sequential variants of Earth's orientation, Earth's surface geometry, and gravitational field. The observations contain the influences of a number of geodynamic processes coming from both the outer space and the Earth [3].

Measuring the dynamics of crust for earthquakes assessment attracts the geodetic approach globally. This is because seismic network configurations are more limited as compared to geodetic network. Small-scale information on crustal deformation was conventionally based on repeated electromagnetic measurements (EDM). Of course, EDM measurement is restricted to inter-visible points over a length of approximately 50 kms [21]. However, current techniques to observe movements of the plates have emerged in cases of long lengths involving thousands of kilometres [22]. The conventional geodesy has now been improved significantly by the application of modern methods and measuring systems such as GNSS, VLBI, SLR [23], InSAR/DInSAR, Satellite Altimetry and Gravimetry [24].

The global and continuous operation of the modern geodetic methods affords high-quality measurements. With these current geodetic methods, there is probability of achieving a high accuracy detection of coseismic deformations such as displacement, strain, geoid, and gravity changes. Such geophysical–geodetic information is relatively valuable for investigating seismic mechanisms, seismic fault inversion, Earth structure, and so on [25]. These observations combined with the conventional measurements based on seismological and/or geological techniques can be analysed further for studying the properties of earthquakes, and the Earth's inner structure, etc., which forms a specific concept of seismological geodesy. The following subsections are focused on GNSS, InSAR/DInSAR, and gravimetry.

2.1 GLOBAL NAVIGATION SATELLITE SYSTEMS

Global Navigation Satellite Systems (GNSS) for world's navigation and positioning emerged in 1960s. Using radio waves as carriers of signals, this system utilizes observed signal travel times to generate distance between satellites and ground receivers [3,26]. With the satellite's orbits and known time, the positions (coordinates) of terrestrial stations can be computed with a certain terrestrial reference system. GNSS is a motion displacement system that is capable of measuring at the longest periods down to the stationary offset at 0 Hz [27]. Nowadays, the GNSS tropospheric and ionospheric delays can be collected through ground-based GNSS networks and space-borne GNSS Radio Occultation [28,29].

GNSS-based measurements have proven to be of great importance in geophysical investigations as a geodetic method for decades [30]. It has significantly influenced the technique of conducting a high-accuracy crustal deformation study. Since the 2004 Sumatra incidence, several GNSS-based approaches have been developed and enhanced to quantify source characteristics for earthquake and tsunami early warning in real-time (e.g., [31—33]). These studies and many others indicate that GNSS affords accurate position time series used to determine space tectonics velocities and/or other earthquake related displacements [24]. Specifically, Ji et al. [34] showed the prospect of dynamic and fixed displacements from high-rate GNSS by deducing the finite fault slip account of the 2003 San Simeon earthquake

(Mw 6.5) in USA. Emore et al. [35] used inversion approach to recover seismic displacements in the 2003 Mw 8.3 Tokachi-Oki earthquake. This technique concurrently estimated the ground displacement from accelerometer data and GPS. Also, Feng et al. [36] employed uninterrupted GPS measurement from 24 stations for studying instant dynamic characteristics of micro displacement before the study of Mw 6.4 Menyuan (in China) earthquake of 2016. The study demonstrated that prior to the event; the horizontal undulatory movements were more than the mean level in the series data, which signify the disturbance feature of regional stress.

2.2 SATELLITE REMOTE SENSING

Remote sensing is fast becoming the most valuable means for conducting different kinds of observations. The reason for this is that it has a high capacity for spotting the spatiotemporal modification of Earth's features [37]. Remote sensing technology is used to capture Earth's information by employing airborne and space-borne sensors [38]. In other words, it consists of collection and interpretation of the target's information without any form of physical contact with the target. Remote sensing application has advanced into a hotspot in earthquake monitoring and forecasting research [39-41]. Satellite-based assessment affords a realistic means of large scale precise and continuous observation of the Earth. For instance, techniques such as InSAR/DInSAR are useful in mapping and evaluating landslide in the post-seismic incident. It allows advances in recognizing, mapping, and estimating surface distortion processes at various scales. Moreover, data obtained from InSAR are used to observe sub-aerial coseismic ground displacements from the earthquake at very high-spatial resolutions.

Earthquake remote sensing actually dated back to the 1970s, when the first satellite imagery was assessed. It was first used not only in structural geology but also for geomorphologic purpose, by mapping active faults as well as structures. This technique in contemporary time is the analysis of active tectonics through the use of alignment analysis [42], as per prior to, and following an earthquake. Satellite Earth Observation sensors employed in active tectonics are active and passive sensors [43]. However, advancement in satellite technology has resulted to a new technique that incorporates active and passive infrared imaging potentials in one chip, which thus results to lighter and simpler double-mode active/passive cameras that are characterized with less power dissipation. Also, remote sensing sensors may be categorized into non-imaging sensors (e.g. spectroradiometers, radiometers, LiDAR, and laser range finder/altimeters), and imaging sensors (e.g. optical imaging, thermal imaging, and radar imaging).

2.2.1 Optical satellite systems

Optical satellite systems use visible and infrared electromagnetic portions (0.4μm - 20μm) for responding to electromagnetic spectrum. Sensors in this category are based on optical technology, which combines lenses, mirrors, and prisms; and are usually used to receive and analyze electromagnetic rays. Generally, an optical sensor measures a physical magnitude of light and interprets it to a readable form for an integrated measuring device. The main categories of optical imaging sensors are: panchromatic, multispectral, and hyperspectral. Panchromatic sensors are responsive to rays in a broadband and produces black and white or gray-scale images. Multispectral sensors are sensitive to rays in a narrow band and create multilayer images that contain brightness and spectral (colour) information of targets under investigation. Hyperspectral sensors are capable of recording data in tens or hundreds of wavelengths or spectra channels in a very narrow and contiguous nature [44].

The new generation of VHR (Very High Resolution) optical images (≤ 1 m) such as WorldView-2 has the capacity of sensing finite alterations on the surface. Of course, coseismic and post-seismic deformations can be sensed through the current optical satellite systems, by using a sub-pixel relationship method.

2.2.2 Thermal satellite systems

Thermal satellite systems use the photons' direct surface contact to sense emitted thermal ray. Thermal sensors basically observe the surface temperature and thermal characteristics of targets by using single or multiple inner temperature references with which to compare the sensed ray in order to link them to absolute radiant temperature. Universally employed thermal imaging systems comprise of infrared (IR) imaging radiometers, imaging spectroradiometers, and IR imaging cameras. Satellite thermal remote sensing has become known as a prospective tool in detection of pre-earthquake thermal infrared (TIR) anomaly in land surface temperature (LST) within or/and around epicentral regions. With satellite TIR data, it is possible to identify large-scale linear structures and short-term disparities of thermal anomalies over tectonic plate boundaries and active faults [45,46]. Of course, the "thermal anomaly" is an enhanced emission of TIR from the Earth's surface preceding the earthquakes usually generated from satellite data [47].

Thermal data in seismic studies was first put to application in Russia in 1985 [40]. Subsequently, various studies have been conducted using satellite-based thermal data such as the AVHRR, MODIS, ASTER, ASAA, and IRIS etc. Generally, there is a correlation between thermal anomaly LST and pre-seismic activity. Various researches demonstrate the suitability of thermal images in earthquake study based on thermal anomalies preceding the earthquakes (e.g., [48,49,50-52]).

2.2.2 Microwave satellite systems

Microwave satellite systems are sensitive to wavelengths which may extend from a few micrometres to meters. Unlike the shorter microwave rays, the longer microwave radiations are not vulnerable to scattering effect of the atmosphere. Thus, they can penetrate cloud cover, fog, haze, and dust. Consequently, they are used for recognizing microwave energy regardless of weather and environmental circumstances. RaDAR is the main familiar type of active microwave sensors. It broadcast a radio signal in the direction of target and senses the backscattered fraction of the signal, thereby creating an image at the microwave level.

Interferometric Synthetic Aperture RaDAR (InSAR) system is used to observe surface deformation with high accuracy in space and time. InSAR affords a number of exceptional potentials for evaluating the deformation of Earth's crust and active processes such as mapping of surface distortions at high resolutions in space over large coverage without requiring monuments on the ground. Also, InSAR is specifically responsive to vertical displacements and has been effectively used with high spatial resolution and accuracy in monitoring landslides, earthquakes, volcanic activities and metropolitan subsidence as well as human-induced deformation due to mining of mineral resources, and extraction of groundwater [53].

The InSAR method employs the discrepancies existing between two SAR images (master and slave) acquired with a nearly identical incidence angle to produce a line of view alteration between locations on earth and the satellite instrument [54]. Merging these SAR images normally creates a phase interference image called an interferogram [55,56]. The phase in SAR is a consistent signal, which contains information on the distance between ground resolution cell and the radar antenna, as well as information about terrain texture in a resolution cell.

There is much research evidence that InSAR technique offers an enhanced platform for remote sensing applications in seismology, and it is considered as one of the greatest means of assessing earthquake related distortions aftershock. Of course, studying coseismic deformation using InSAR, which can usually acquire large-scale minor-magnitude location alteration is a unique approach for monitoring crustal deformation, especially across active fault belts. For instance, InSAR from the ERS-1 satellite was used for geodetic measurement by Massonnet et al. [57] to identify the permanent coseismic deformation stimulated by the 1992 Mw 7.3 Landers earthquake in USA. Result of geodetic deduction of the earthquake based on InSAR data was extremely in line with the field observation. Also, Massonnet et al. [58] used Radar Interferometry for mapping deformation as a result of the Landers earthquake, in the year after its incidence. Elliot et al. [59] used diverse data comprising InSAR, field mapping, aerial photographs, LiDAR DEM, and teleseismic body-wave, etc., to evaluate the faulting behaviour in the New Zealand Mw 7.1 Garfield of 2010 and Mw 6.3 Christ Church earthquake of 2011.

2.3 GRAVIMETRY

Gravimetry is of great importance for geodesy, as gravity variations influence Earth's rotation and orientation systems. Moreover, gravity field contains geophysical information, which is extremely invaluable for modelling geodynamic processes [3]. Gravimetry in studies involving tectonic plate boundaries and especially in regions of seismotectonic activity provides extra important information to geometric deformation monitoring.

Observation of gravity can be conducted directly by using ground-based or space-based techniques, or indirectly inferred from quantities that has direct relationship to gravity, such as sea surface topography [60]. Apart from the campaign gravimetry, the super-conduct gravimetry essentially provides a new understanding into the geophysical incidence, which has productively recorded the free oscillation of the earth due to large earthquake [61]. Evidence in the literature demonstrates the potency of gravimetry in seismic assessment. For instance, Shen et al. [62] carried out a study on the distribution of gravity changes connected to coseismic deformation, showing how the geometry of fault and medium structure affects the synthetic surface gravity. Chen et al. [63] conducted a study on the Mw 7.8 Nepal earthquake that occurred on 25 April 2015 using absolute gravimetric stations. Result indicates a distinct gravity increase relatively to `the long-wavelength secular trends of decrease in gravity over the Tibetan Plateau. Of course, this may be connected to interseismic mass dynamics around the locked plate interface under the Himalayan-Tibetan Plateau.

In recent years, various gravity observations have shown clear coseismic signals (more than a few μGal or 10–8 m/s2) of large earthquakes, such as the Great 2004 Sumatra-Andaman earthquake (Mw 9.1) and the 2011 Tohuku earthquake (Mw 9.0) [64,65]. These include the dynamic gravity measurements facilitated by various gravity-based tools including the GRACE, GOCE, and other space missions. These gravity changes are consistent with deformations and the related mass alterations of these earthquakes [66]. GRACE is the first and a higher resolution dedicated satellite mission that affords an effective result in the form of global gravity fields at 30 days interval [67], and its data has been used for various studies. Okal [68] used satellite altimetry (ERS-1 and TOPEX/POSEIDON) to investigate the ocean surface deformation. This was actually used with respect to seven tsunamigenic earthquakes including Nicaragu (1992), Japan Sea (1993), Java (1994), Kuriles (1994), Chile (1995), Biak, Indonesia (1996), and Chimbote, Peru (1996). A positive tsumani wave field was identified as per the Nicaraguan tsunami, which was detected at 15°S, 106°W nearly five hours after origin. Zero-to-peak amplitude of 8 cm was observed. Also, the recognition of the Chilean tsunami was uncertain due to a large spectral scatter of the reference tracks. Furthermore, Han et al. [69] studied the 2011 great Tohoku-Oki earthquake and noticed significant changes in inter-satellite distance after the earthquake.

4. CONCLUSION

Accurate information on deformation of the Earth's crust is crucial to promptly identify spatiotemporal behaviour of the Earth. Crustal deformation assessment by geodetic technique has become very significant due to its speedy advancement, as well as observation accuracy and consistency. This review has demonstrated that geodetic data afford a useful complementary technique for understanding seismic hazard.

Currently, global thrust on crustal deformation studies is on rise following the emergence of advanced technologies. Long-term observation using GNSS affords three-dimensional deformation time series of a location. Also, the availability of enormous volume of high-resolution imageries has altered the way that scientists respond to major geodynamic phenomenon. Furthermore, the enhancement of Earth Observation information and techniques in the recent decades presents a manner for observing crustal motions with reliable accuracy and spatial extent, as well as long-term seismic catastrophe on the decadal to millennial scale. InSAR data can be used to effectively measure deformation transients with periods of few-to-several tens of days. InSAR collection of enormous quantity of radar scenes affords extended temporal baselines and a larger amount of prospects to form interferometric pairs with shorter geometric baselines which improve coherence, as such; their observations can harmonize seismological observation of earthquakes. During the SAR data processing, the GPS data are very useful to model non-tectonic signals, and therefore GPS must be used in synergy with InSAR methods whenever possible. Gravimetry essentially provides a new understanding into the geophysical incidence, which has productively recorded the free oscillation of the earth due to the large earthquake. In the near future, there will be further improvement in our ability to measure tectonic deformation using satellite geodetic techniques, particularly from the combining interfrometric SAR and GNSS.

REFERENCES

1. Han, S. C, Shum, C. K., Bevis, M., Ji C., and Kuo, C. K. (2006). Crustal dilatation observed by GRACE after the 2004 Sumatra-Andaman Earthquake. Sci., 313, 658–662.
2. Elliot, J. R., Walters, R. J., and Wright, T. J. (2016). The role of space-based observation in understanding and responding to active tectonics and earthquakes. Nat. comm. 7, 13844.
3. Torge, W., and Muller, J. (2012). Geodesy, fourth ed. De Gruyter, Berlin.
4. Attia, G. F. (2014). Studies of tectonic motion from Helwan-satellite laser ranging station. Int. J. Astro. and Astrophys. 4, 607-613.
5. Donnellan, A., Arrowsmith, R., and Delong, S. (2017). Spatio-temporal mapping of plate boundary faults in California using geodetic imaging. Geosci. 15, 1-26.
6. Butler, R.F. (1992). Applications to paleogeography. Paleomagnetism: Magnetic domains to geologic terranes. Blackwell, Uk.
7. Cande, S. C., and Stegman, D. R. (2011). Indian and African plate motions driven by the push force of the Re´union plume head. Nature 475, 47–52.
8. Gerya, T.V., Stern, R.J., Baes, M., Sobolev, S.V., Whattam, S.A. (2015). Plate tectonics on the Earth triggered by plume-induced subduction initiation. Nature, 527, 221.

9. White, R., and Mckenzie, D. (1989). Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. J. Geophy. Res. 94, 7685–7729.
10. Hammond, W. C., Lib, Z., Plaga, H. P., Kreemera, C., and Blewitt, G. (2010). Integrated InSAR and GPS studies of crustal deformation in the western great basin, western United States. Int. Arch. Photogramm., Rem. Sens. and Spat. Inf. Sci., XXXVIII.
11. Tatcher, W. (2009). How the Continents Deform: The Evidence From Tectonic Geodesy. Annu. Rev. Earth Planet. Sci. 37, 237–62.
12. Allen, R. M., Gasparini, P., Kamigaichi, O., and Bose, M. (2009). The status of earthquake early warning around the world: An introductory overview. Seism. Res. Lett. 80, 682-693.B¨urgmann, R., Rosen, P. A., and Fielding, E. J. (2000). Synthetic aperture radar interferometry to measure Earth's surface topography and its deformation. Annu. Rev. Earth Planet. Sci. 28, 169–209.
13. Geiß, C., and Taubenböck, H. (2013). Remote sensing contributing to assess earthquake risk: from a literature review towards a roadmap. Nat. Hazards, 68, 7-48.
14. Reddy, C.D., Arora, S.K., Sunil, P.S., and Prajapati, S.K. (2011). Earthquake Related Deformation Cycle: Perspectives from 2004 Sumatra and 2010 Chile Mega-Earthquakes . Disaster Advances, 4 (2), 13-21.
15. Barbot, S., Lapusta, N., and Avouac, J. P. (2012). Under the hood of the earthquake machine: toward predictive modelling of the seismic cycle. Sci. 336, 707-710.
16. Cohen, S. C. (1984). Postseismic deformation due to subcrustal viscoelastic relaxation following dip-slip earthquakes. J. Geophys. Res. 89, 4538-4544.
17. Masterlark, T., Demets, C., Wang, H. W., Sanchez, O., and Stock, J. (2001). Homogeneous vs heterogeneous subduction zone models: coseismic and postseismic deformation, Geophys. Res. Lett. 28, 4047-4050.
18. Melbourne, T., Webb, F., Stock, J., and Reigber, C. (2002). Rapid postseismic transients in subduction zones from continuous GPS, J. Geophys. Res. 107, E1-E10.
19. Reid, H. F. (1910). The mechanics of the earthquake, vol. II. In: Lawson A.C. The California earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission, Carnegie Institution of Washington, Washington, DC, USA, Publ. 87, 192.
20. Avouac, J. P. (2015). From Geodetic imaging of seismic and aseismic fault slip to dynamic modeling of the seismic cycle. Annu. Rev. Earth Planet. Sci. 43, 233-271.
21. Savage, J. C, and Prescott, W. H. (1973). The precision of theodolite distance measurement for determining fault movements. J. Geophys. Res. 8, 6001-6007.
22. Clark, T. A., Gordon, D., Himwich, W. E., Mallama, C. M., Mallama, A., and Ryan, J. W. (1987). Determination of relative site motions in the western United States using Mark III very long baseline Interferometry. J. Geophys. Res. 92, 741-750.
23. Onyeka, E. C. (2009). Monitoring regional and local earth dynamics using space geodesy techniques. Nig. J. Surv. Geoinf. 2, 74-86.
24. Zhou, S., and Wu, Y. (2013). Earthquake geodesy for fifty years- thinking on subject development. J. Geod. Geom. Chn. 2, 1-7.
25. Wenke, S. U. N. (2014). Recent advances of computing coseismic deformations in theory and applications. Earthq. Sci. 27, 217–227.
26. Ghilani, C. D., and Wolf, P. R. Elementary Surveying: An Introduction to Geomatics, 12 ed. New Jersey: Pearson Education International (2008).
27. Melgar, D., Bock, Y., Sanchez, D., and Crowell, B. W. (2013). On robust and reliable automated baseline corrections for strong motion seismology. Journal of Geophysical Research: Solid Earth, 118, 1177–1187.
28. Jin, S. G., Wang, J., Zhang, H., and Zhu, W. (2004). Real-time monitoring and prediction of the total ionospheric electron content by means of GPS observations. Chin. Astron. Astrophys. 28, 331–337.
29. Jakowski, N., Hoque, M. M., and Mayer, C. (2011). A new global TEC model for estimating transionospheric radio wave propagation errors. J. Geodesy, 85 965–974.

30. Segall, P., and Davis, J. L. (1997). GPS applications for geodynamics and earthquake studies. Annu Rev Earth Planet Sci, 25, 301–36.
31. Colombelli, S., Allen, R. M., and Zollo, A. (2013). Application of real-time GNSS to earthquake early warning in subduction and strike-slip environments, J. Geophys. Res., 118, 3448–3461.
32. Grapenthin, R., Johanson, I. A., and Allen, R. M. (2014). Operational real-time GNSS-enhanced earthquake early warning. J. Geophys. Res. Solid Earth, 119, 7944–7965.
33. Crowell, B. W., Schmidt, D. A., Bodin, P., Vidale, J. E., Gomberg, J., Hartog, J. R., Kress, V. C., Melbourne, T. I., Santillan, M., Minson, S. E., and Jamison, D. G. (2016). Demonstration of the Cascadia G-FAST Geodetic Earthquake Early Warning System for the Nisqually, Washington, Earthquake. Seism. Res. Lett. 87,
34. Ji, C., Larson, K, M., Tan, Y., Hudnut, K. W., and Choi, K. (2004). Slip history of the 2003 San Simeon earthquake constrained by combining 1-Hz GPS, strong motion, and teleseismic data. Geophys. Res. Lett. 17, 608.
35. Emore, G. L., Haase, J. S., Choi, K., Larson, K. M., and Yamagiwa, A. (2007). Recovering seismic displacements through combined use of 1-Hz GPS and strong-motion accelerometers. Bull. Seimol. Soc. Am. 97, 357–78.
36. Feng, W., Ren, J., and Jiang, Z. (2016). GPS station short-term dynamic characteristics of micro displacement before Menyuan M6.4 earthquake. Geodesy and Geodynamics. 7, 237-244.
37. Weng, Q. remote sensing and GIS integration, theories, methods, and applications. New York: McGraw-Hill Companies, Inc. (2010).
38. Duggal, S. K. (2004). Surveying, second ed. New Delhi: Tata Mc Graw-Hill;. P. 1-435.
39. Parrot, M. (1995). Use of satellites to detect seismo-electromagnetic effects. Adv Space Res 15, 27–35.
40. Ouzounov, D., and Freund, F. (2004). Mid-infrared emission prior to strong earthquakes analyzed by remote sensing data. Adv Space Res 33, 267–273.
41. Shen, X., Wu, Y., and Shan, X. (2007). Remote sensing application in earthquake science and general propose for China earthquake satellite project. Int Prog Earthq. Sci. 8, 38–45.
42. Lillesand, T., Kiefer, R. W., and Chipman, J. Remote sensing and image interpretation, seventh ed. UK: John Wiley & Sons, (2014).
43. Omali, T U. (2018). Prospects of satellite-enhanced forest monitoring for Nigeria. Int. J. Scientific & Eng. Res. 9, 383-388.
44. Filizzola, C., Pergola, N., Pietrapertosa, C., and Tramutoli, V. (2004). Robust satellite techniques for seismically active areas monitoring: a sensitivity analysis on September 7, 1999 Athens's earthquake, Phys. Chem. Earth, 29, 517-527.
45. Tramutoli, V., Cuomo, V., Filizzola, C., Pergola, N., and Pietrapertosa, C. (2005). Assessing the potential of thermal infrared satellite surveys for monitoring seismically active areas: The case of Kocaeli (İzmit) earthquake, August 17, 1999, Remote Sens. Environ., 96, 409-426.
46. Freund, F., Keefner, J., Mellon, J. J., Post, R., Takeuchi, A., Lau, B. W. S., La, A., and Ouzounov, D. (2005). Enhanced Mid-Infrared Emission from Igneous Rocks under Stress. Geophysical Research Abstracts, 7, 09568.
47. Tronin, A. A. (2000). Thermal IR satellite sensor data application for earthquake research in China. Int. J. Remote Sensing, 21, 3169-3177.
48. Quang, Z., Xu, X., and Dian, C. (1991). Thermal infrared anomaly precursors of impending earthquakes. Chin. Sci. Bull. 36, 319-323.
49. Gorny, V. I., and Shilin, B. V. Thermal method of remote sensing for study of natural resources, Proceedings of the 18th Annual Conference of the Remote Sensing Society, 1992, University of Dundee, 15-17th September 1992. Cracknell, A. P., AND VAUGHAN, R. A. (ed.), (1992), 245-263.

50. Tronin, A. A. (1996). Satellite thermal survey-a new tool for the study of seismoactive regions. Int. J. Remote Sensing, 17, 1439-1455.
51. Saraf, A. K., and Choudhury, S. (2005). Earthquakes and thermal anomalies. Geosp. Today, 2, 18-20.
52. Hu B., Wang, H. S., Sun, Y. L., Hou, J. G., and Liang, J. (2014). Long-term land subsidence monitoring of Beijing (China) using the small baseline subset (SBAS) technique. Rem. Sens., 6, 3648–3661.
53. Tolomei, C., Salvi, S., Merryman, Boncori, J. P., and Pezzo, G. (2014). InSAR measurement of crustal deformation transients during the earthquake preparation processes: a review. Bull. Geof. Teor. Appl. 56.
54. Zebker, H. A., and Goldstein, R. M. (1986). Topographic Mapping from Interferometric SAR Observations. Journal of Geophysical Research, 91, 4993-4999.
55. Massonnet, D. (1997). Satellite radar interferometry. Scientific American, 276, 46-53.
56. Okeke, F. I. InSAR Operational and Processing Steps for DEM Generation. 5th FIG Regional Conference Accra, Ghana, March 8TH-11TH, (2006).
57. Massonnet, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K., and Rabaute, T. (1993). The displacement field of the Landers earthquake mapped by radar interferometry. Nature, 364, 138-142.
58. Massonnet, D., Feigl, K., Rossi, M., and Adragna, F. (1994). Radar interferometric mapping of deformation in the year after the Landers earthquake. Nature, 369, 227–230.
59. Elliot, J. R., Nissen, E. K., England, P. C., Janckson, J. A, Lamb, S., et al. (2012). Slip in the 2010-2011 Canterbury earthquakes, New Zealand. J. Geophys. Res. B3, B3401.
60. Van Camp, M., De Viron, O., Watlet, A., Meurers, B., Francis, O. and Caudron, C. (2017). Geophysics from terrestrial time-variable gravity measurements. Reviews of Geophysics, 55, 938–992.
61. Xue, X., Hu, X., Hao, X., and Liu, L. (2012). Constraining focal mechanism of the 2011 Tohoku earthquake by gravity observations. Chin J Geophys, 55, 3006–27.
62. Shen, C., Li, H., and Tan, H. (2010). Simulation of coseismic gravity changes and deformation effect of Wenchuan Ms 8.0 earthquake. Geodesy Geodyn. 1, 8–14.
63. Chen, S., Liu, M., Xing, L., Xu, W., Wang, W., Zhu, Y., and Li, H. (2016). Gravity increases before the 2015Mw 7.8 Nepal earthquake, Geophys. Res. Lett. 43, 111–117.
64. Chen, J. L., Wilson, C. R., Tapley, B. D., and Grand, S. (2007). GRACE detects coseismic and postseismic deformation from the Sumatra-Andaman earthquake, Geophys. Res. Lett. 34, L13302.
65. Wang, L., Shum, C. K., and Simons, F. J. (2012). Coseismic and postseismic deformation of the 2011 Tohoku-Oki earthquake constrained by GRACE gravimetry, Geophys Res Lett. 39, L07301.
66. Fuchs, M. J., Bouman, J., Broerse, T., Visser, P., and Vermeersen, B. (2013). Observing coseismic gravity change from the Japan Tohoku-Oki 2011 earthquake with GOCE gravity gradiometry, J. Geophys. Res. Solid Earth, 118, 5712–5721.
67. Tapley, B. D., Bettadpur, S., Watkins, M., and Reigber, C. (2004). The gravity recovery and climate experiment: mission overview and early results. Geophys. Res. Lett. 31, 1-4.
68. Okal, E. A. (1999). Tsunami detection by satellite altimetry. J. GEOPHY. RES. 104, 599-615.
69. Han, S.-C., Sauber, J., and Riva, R. (2011). Contribution of satellite gravimetry to understanding seismic source processes of the 2011 Tohoku-Oki earthquake, Geophys. Res. Lett. 38, L24312.