

Assessment of Crustal Deformation in Earthquake Process: An Overview

ABSTRACT

Crustal deformation involving displacements of Earth mass is an essential variable used in observing and modelling seismic activities. Various approaches especially the geodetic technique for measurement at a predetermined level of repetitions on the Earth is used to observe crustal deformation. The utilization of geodetic systems has significantly enhanced the manner by which crustal movement is being monitored and managed. An obvious indication is the reasonable level of accuracy, and the substantial spatiotemporal coverage achievable with the space-based technique. This paper is aimed at reviewing existing literature on 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, monitoring, seismic, tectonics

1. INTRODUCTION

The Earth's crust is under the influence of both internal and external forces, which are dominated by the gravitational force, and consequently, its surface is in a constant modification. The atmospheric and hydrological components can cause its distortion 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 phenomena. 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 crust's surface 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]. 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 that 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. Merging different poles of diverse ages in a specific plate to create noticeable polar motion paths provides a technique for comparing the movements of diverse plates over time [6]. Though plate motion is used to explicate majority of the Earth's surface features, 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 movements link it to large convection currents in the upper mantle, which are transferred via the asthenosphere. Arthur Holmes and 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] attributed tectonic motion to mantle plumes, stating that they can exert a substantial force on plates. According to their assumption, if the head of a growing plume impinges on the base of a tectonic plate long after supercontinent breakup and distribution, 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 ocean ridges takes place with plate motion as a result of the higher elevation of plates at the 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.

2. METHODS OF CRUSTAL DEFORMATION ASSESSMENT

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]. Generally, there are four chronologically diverse stages in seismic sequence within an active fault (see Reddy et al. [14]) (i.e., 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. Studying coseismic stage is essential 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 through which the material deforms due to the abrupt coseismic release of strain. It exists for many years, 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].

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. 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]. With geodesy, it is possible to deduce the fault's geometric characteristics and the spread of slip. Also, we can compute the related moment discharge by using elastic displacement principle.

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. 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 international and constant operation of the modern geodetic methods affords high-quality measurements. Modern geodetic methods offer the probability of achieving a high accuracy in detecting coseismic deformations such as displacement, strain, geoid, and gravity changes. Such geophysical-geodetic information is relatively valuable for investigating seismic mechanisms, seismic fault inversion, and Earth structure [25]. These observations joined with the conventional measurements based on seismological or geological methods 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.

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, it 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 to the stationary offset at 0 Hz [27]. Nowadays, the GNSS tropospheric and ionospheric delays are improved using ground-based GNSS grids 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 [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 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, signifying 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 its 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 an essential area 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 event. 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 employed in structural geology and for geomorphologic purpose, by mapping active faults and structures. This technique in contemporary time is the study of active tectonics through the usage 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 microwave imaging).

2.2.1. Imaging sensors

Optical satellite systems use visible and infrared electromagnetic portions ($0.4\mu\text{m}$ - $20\mu\text{m}$) 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 analyse electromagnetic rays. Generally, an optical sensor measures a physical magnitude of light and interprets it to a readable form in an incorporated 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 senses 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 very narrow and contiguous spectral bands [44]. The new generation of VHR (Very High Resolution) optical imagers ($\leq 1\text{ m}$) 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.

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. Thermal remote sensing has become known as a prospective tool for detection of pre-earthquake thermal infrared (TIR) anomaly in land surface temperature (LST) within or around epicentral regions. Satellite TIR data is used 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 prior to 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. Hence various researchers have demonstrated the suitability of thermal images in earthquake study based on thermal anomalies preceding the earthquakes (e.g., [48,49,50-52]).

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 atmospheric scattering effect. 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 spatiotemporal 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] employed InSAR for mapping deformation related to 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 spread 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] carried out an investigation on the Mw 7.8 Nepal earthquake of 25th 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/s^2) of large earthquakes, such as the Great 2004 Sumatra-Andaman earthquake (Mw 9.1) and the 2011 Tohoku 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 used with respect to seven tsunamigenic earthquakes

including Nicaragua (1992), Japan Sea (1993), Java (1994), Kuriles (1994), Chile (1995), Biak, Indonesia (1996), and Chimbote, Peru (1996). A positive tsunami 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 the Earth's crustal deformation 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 rising 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 are effective for efficient observation of deformation transients within 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 interferometric SAR and GNSS.

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