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A Comprehensive Review of the Studies of Deformation Due to Seismic Sources

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Abstract:
Surface deformation produced by earthquakes and the seismic cycle is primary observable that links geodesy to fault physics, rheology and seismic hazard. It provides a direct window into the mechanical processes that govern the seismic cycle. Observations from Global Navigation Satellite Systems (GNSS), Interferometric Synthetic Aperture Radar (InSAR), leveling, and gravity missions constrain the accumulation and release of strain across fault systems. This review summarizes common modelling frameworks viz. elastic dislocations, viscoelastic and poroelastic relaxation, and frictional/afterslip models; observational methods like InSAR, GNSS, leveling, gravity, and recent advances in joint inversion and numerical simulation. It highlights representative case studies, and identifies outstanding challenges and opportunities in the study of deformation from seismic sources.

Key Words: dislocation, coseismic, postseismic, viscoelastic relaxation, seismic sources.

1. Introduction

Earthquakes represent sudden stress release along faults. But the processes of strain accumulation and relaxation extend far beyond the brief moment of rupture. The deformation field produced across the seismic cycle including interseismic strain buildup, coseismic offsets, and postseismic transients and provides a continuum of information about lithospheric mechanics and seismic hazard. For coseismic processes, the analytic elastic dislocation models, pioneered by Okada [1], remains the workhorse for inferring finite fault slip. For the postseismic epoch, a combination of afterslip, viscoelastic relaxation and poroelastic rebound is generally required to explain observations with important dependence on spatial scale and time after rupture.

Modern geodetic tools like GPS/GNSS, radar interferometry (InSAR), leveling, and gravity missions like GRACE/GRACE-FO records the crustal response to stress changes produced throughout the seismic cycle. They capture these processes with unprecedented resolution,

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enabling both near-real-time hazard assessment and deeper insight into crust and mantle rheology [2-3]. These measurements allow estimation of coseismic slip distributions, quantification of interseismic strain accumulation and fault coupling, and characterization of transient postseismic processes that evolve from days to decades.

Linking geodetic fields to subsurface fault processes requires forward models (elastic and viscoelastic) and inverse methods that account for observational errors and modelling non-uniqueness. Recent advances in data acquisition, atmospheric corrections, and joint inversion frameworks allow improved characterization of deformation patterns across the seismic cycle. However, attribution of observed deformation to distinct mechanisms remains challenging because of model non-uniqueness, environmental noise, and rheological heterogeneity in the lithosphere and asthenosphere.

This review synthesizes an integrated overview of modelling strategies, analytical studies, observational approaches and methodological frontiers for the study of deformation due to seismic sources. In section 2, various modelling approaches are presented. Section 3 highlights different types of deformations. In Section 4, modern observational approaches are discussed. In section 5, the challenges and opportunities in the study are highlighted. The review is summarized in Section 6.

2. Modelling approaches

Seismology is the study of the generation, propagation, and recording of elastic waves in the Earth, as well as the sources that produce them. Seismic waves are elastic disturbances that spread outward from a source due to sudden stress imbalances within or on the Earth's surface. The sources of these disturbances can be natural or human-made, and nearly any sudden deformation of the medium can generate seismic waves.

The most significant sources for global seismology are shear faulting or earthquake faulting, but many others are of scientific interest. The sources include loads on the surface, buried explosions, magma movements, hydrological circulations, abrupt phase changes, mine bursts, and rock spallation. To represent these complex physical processes, idealized force systems are used in mathematical and physical models.

Faults are the planar surfaces across which relative motion occurs during earthquake. Faulting means slippage between two blocks of materials. A standard nomenclature has evolved for describing fault orientation and slip direction. The detailed description about seismic sources is given in the classical texts: Aki and Richards [4], Ben-Menahem and Singh [5], Lay and Wallace [6] and Stein and Wysession [7].

As the rupture progresses, stored strain energy is released as both seismic waves and heat, until fault motion ceases. For long-wavelength seismic waves, the rupture area is small relative to the wavelength and can be approximated as a point source. By contrast, short-wavelength waves are sensitive to the finite size of the fault and the detailed slip process, requiring more complex finite-source models.

Seismologists study both the waves and their sources to better understand Earth's interior. Their study integrates the study of natural and artificial seismic sources, elastic wave propagation, and mathematical modelling. Among the most critical theories, elastic rebound and dislocation theory provide a foundation for understanding earthquake mechanics, seismic wave generation, and their role in probing Earth's internal structure.

2.1 Elastic dislocation theory

A key framework for understanding earthquake generation is elastic dislocation theory. It proposes that faulting occurs when accumulated elastic strain exceeds the static friction resisting motion. Slip initiates at a point, called the hypocenter, and the rupture front spreads across the fault. This separates regions that have slipped from those still locked, with the rupture's growth governed by both space and time. The slip function describes the relative motion of fault blocks during this process.

Okada's [1] closed-form solutions for dislocations in a homogeneous elastic half-space remain central to earthquake geodesy. These models represent fault slip as rectangular or triangular elements embedded in a homogeneous elastic medium and are used to generate closed form Green's functions for both forward and inverse modelling. They are foundational for modelling coseismic and many interseismic deformation problems. Despite assumptions of homogeneity and planar fault geometry, their computational efficiency and analytic clarity make them invaluable and first choice for finite-fault inversions and many hazard applications [3].

2.2 Triangular dislocation elements (TDEs) methods

To handle complex fault geometries and non-uniform slip, triangular dislocation elements extend Okada's framework [3]. TDE implementations allow flexible meshing of faults and reduce geometric biases in inversions, though they are computationally more demanding. Their efficient algorithms and open-source code enable large inversions and exact surface displacement calculations.

2.3 Viscoelastic relaxation models

Viscoelastic models simulate the viscous flow of the lower crust and upper mantle in response to coseismic stress changes. Postseismic deformation that evolves over months to centuries often requires viscoelastic rheologies. Layered Maxwell or Burgers rheologies are common representations [8]. Finite element methods (FEM) and semi-analytic approaches extend these models to three-dimensional rheologic structures and topography. The results are very sensitive to assumed mantle viscosities and crustal layering, which affects the partitioning between near-field and far-field signals. Model predictions are highly sensitive to mantle viscosity structure, making observational constraints essential.

2.4 Poroelastic rebound models

Fluid migration and pore pressure diffusion in the upper crust cause poroelastic rebound that can mimic shallow afterslip in early postseismic deformation. It is important at very short timescales where fluid diffusion in shallow crustal poroelastic media produces transient deformation. These effects are usually short-lived but important to distinguish for accurate hazard assessment [9].

2.5 Afterslip models

Afterslip is modeled either kinematically or using rate-and-state friction laws. Afterslip typically occurs on velocity-strengthening regions of the fault and can release a substantial fraction of coseismic stress [10]. Afterslip is often invoked to explain prompt near-fault postseismic motion. Joint kinematic and physics-based inversions can help attribute deformation to fault slip rather than deeper viscous flow. Dense GNSS/InSAR data near fault traces are essential for constraining these models.

3 Deformations

3.1. Coseismic deformation

Coseismic deformation represents the most abrupt surface signal in the seismic cycle. The coseismic fault movement, which usually occurs in the brittle upper crust, causes a sudden stress increase below the brittle-ductile transition [11]. This stress that is coseismically imposed on the lower crust and lithospheric mantle is relaxed by viscoelastic flow, a process called postseismic relaxation [12]. Coseismic slip inversions typically use elastic Green's functions and penalized least squares or Bayesian frameworks to infer spatial slip distributions and uncertainties. High-resolution InSAR maps constrain the rupture surface pattern; GNSS provides robust long-wavelength constraints and temporal behaviour at stations. For instance, analyses of the 2011 Tohoku earthquake combined multiple SAR tracks with GNSS offsets to infer up to 50 m of slip on the megathrust [13]. Combined inversions benefit from the complementary strengths: InSAR provides dense spatial sampling, while GNSS anchors long-wavelength offsets and helps correct atmospheric artifacts. Limitations include trade-offs between slip depth and fault dip, smoothing choices that bias slip localization, and atmospheric/orbital error residuals InSAR data [14]. Robust results often test model sensitivity to different smoothing, parameterizations (rectangles vs triangles), and data subsets.

3.2. Postseismic deformation

Postseismic deformation is multi-mechanism and time-dependent. Postseismic deformation unfolds over timescales of days to decades and is governed by a superposition of processes. The three primary processes are:

(i) **Afterslip (aseismic slip on the fault):** typically dominates near the fault in the early postseismic period (days to years), producing deformation similar in pattern to coseismic slip but often more spatially diffuse. They are often well explained by afterslip on the downdip or along-strike extensions of the coseismic rupture [10]. Afterslip models can be kinematic or frictional (rate-and-state). Kinematic inversions demonstrate that afterslip tends to concentrate where frictional properties favour velocity-strengthening behaviour.

(ii) **Viscoelastic relaxation:** Viscous flow in the lower crust and upper mantle relaxes coseismic stresses, often producing broader-wavelength, sometimes opposite-sense motion inland of megathrusts and dominating at longer times and larger distances from the rupture. The timing and amplitude are sensitive to mantle viscosity structure and layering.

Postseismic viscoelastic relaxation in the lower crust and/or lithospheric mantle typically acts on local to regional spatial scales and on timescales of years to decades depending on the viscosity of the lithospheric layers [15-18].

Sun et al. [8] emphasize that viscoelastic relaxation should be expected after very large megathrust events and can bias simple afterslip inversions if neglected.

Far-field deformation after large subduction earthquakes, such as the 2010 Maule and 2011 Tohoku events, is dominated by viscoelastic relaxation. Distinguishing these signals from afterslip requires wide-aperture GNSS networks and long observation windows.

(iii) Poroelastic rebound: fluid diffusion and pore pressure equilibration in the shallow crust cause early, often short-lived deformation that can be misattributed to shallow afterslip if only surface displacements are considered. Short-lived deformation observed in the first months after rupture can be attributed to poroelastic rebound, especially in sedimentary basins. Distinguishing this mechanism is crucial because it influences inferred shallow slip distributions [9]. Distinguishing mechanisms requires multi-temporal, multi-instrument data and model comparisons. Spatial partitioning (near-fault vs far-field) and temporal evolution (fast early decay vs slower, long-term trends) are key diagnostics: afterslip often decays rapidly and is spatially concentrated near the rupture, whereas viscoelastic signals grow or persist at larger distances and over longer timescales. Joint inversions that explicitly include both fault slip and viscoelastic rheologies, and that explore model parameter trade-offs, produce the most defensible attributions; several recent studies [19-21] present frameworks and case examples applying this strategy.

3.3. Interseismic deformation and fault coupling

Interseismic geodetic rates are inverted to estimate slip deficit and fault coupling which is the key inputs to seismic hazard. These inversions usually assume a locked/partially coupled fault embedded in an elastic or layered viscoelastic Earth. Long-wavelength signals and steady-state plate motion must be separated from localized strain accumulation. Persistent scatterer InSAR and GNSS integration has revealed complex along-strike variations in coupling for subduction zones and crustal faults, with implications for rupture segmentation and earthquake cycles.

Between large earthquakes, strain accumulates on locked fault patches. GNSS velocity fields and InSAR time series are inverted to estimate slip deficits and coupling variations. Along-strike variability in coupling has been demonstrated in subduction zones such as Cascadia and Chile [22]. These estimates feed directly into probabilistic seismic hazard models.

4 Observational methods and data characteristics

4.1 Global Navigation Satellite Systems (GNSS)

GNSS networks provide precise, continuous three-dimensional displacement records at sub-centimetre precision. Dense arrays in tectonically active regions, such as Japan or California, have revealed both steady interseismic strain accumulation and transient slip events [23]. The long-wavelength sensitivity of GNSS makes it an indispensable complement to InSAR, which is prone to atmospheric biases over similar scales. Continuous and campaign GNSS provide precise, time-resolved 3-D station displacements and velocities.

4.2 Interferometric Synthetic Aperture Radar (InSAR)

InSAR provides dense, spatially continuous measurements of ground displacement in the radar line-of-sight (LOS). Single interferograms capture coseismic deformation with high spatial detail, while multi-temporal approaches such as Persistent Scatterer (PS) and Small Baseline Subset (SBAS) methods extract long-term time series for both interseismic rates and transient signals and reduce atmospheric and orbital errors [24-25]. Atmospheric delays (troposphere, ionosphere) and decorrelation, however, can introduce spurious long-wavelength signals that require correction or validation using empirical models or GNSS data.

4.3 Gravity and leveling

Satellite gravity missions (GRACE, GRACE-FO) record mass redistribution following large earthquakes, providing constraints on deep viscoelastic processes not accessible through surface displacement alone. Leveling and tiltmeters, while less widely deployed today, remain valuable for historical or local-scale deformation records.

4.4 Data integration

Joint analysis of GNSS and InSAR data improves both spatial coverage and wavelength sensitivity, reducing inversion non-uniqueness. Data fusion approaches that integrate gravity observations further enhance constraints on lithospheric rheology and mass redistribution.

5. Challenges and Opportunities: Challenges include contamination by hydrological loading, atmospheric noise in InSAR, and simplifying assumptions about rheology. Layered or laterally varying viscoelastic models suggest that coupling inferences based on purely elastic assumptions may be biased [26]. Some suggestive measures are:

1. **Non-uniqueness between mechanisms.** Afterslip, viscoelastic relaxation and poroelastic rebound remain difficult to separate without dense and long-term observations and joint inversion frameworks; improved physical priors and multi-observable approaches (including gravity and seismicity) can help.
2. **Rheologic heterogeneity.** Lithospheric viscosity varies laterally, and capturing these variations requires joint inversions constrained by seismic tomography and mineral physics.
3. **Atmosphere and environmental noise.** Advanced atmospheric corrections, machine-learning-assisted filtering, and multi-sensor fusion are promising avenues to improve the signal-to-noise in InSAR time series [27].

4. **High-resolution, near-fault observations.** New SAR constellations, dense GNSS (low-cost arrays) and improvements in unwrapping should enhance detection of small shallow slips and slow slip transients**.**

Best practice in inversion includes using physically meaningful parameterizations (e.g., triangular elements or adaptive meshes); incorporating prior information and regularization transparently; running sensitivity tests to smoothing/parameter choices, and doing model comparison (afterslip-only, viscoelastic-only, combined). Bayesian approaches provide posterior uncertainty estimates but can be computationally demanding [28]**.** Recent algorithmic work improves efficiency for TDEs and hybrid inversions; open code bases (TDE libraries, FEM packages) encourage reproducibility. Incorporating GNSS constraints in atmospheric correction for InSAR and using both ascending and descending SAR tracks reduce ambiguities. Robust slip inversions and rheologic models require explicit consideration of uncertainties. Regularization choices strongly influence slip distributions; sensitivity testing and model comparison are essential.

6. Conclusions

Surface Deformation studies remain central to understanding earthquake mechanics and seismic hazard. Analytic elastic dislocation models provide a robust baseline for coseismic inversions, while viscoelastic and poroelastic models extend interpretations into the postseismic and interseismic phases. Integration of dense GNSS networks, advanced InSAR processing, and gravity data is revolutionizing our ability to constrain both fault slip and lithospheric rheology. Nonetheless, challenges in mechanism separation, non-uniqueness, and noise correction highlight the importance of multi-sensor data and robust modelling frameworks. Continued advances in observation, computation, and integration will be crucial and promise to refine our understanding of the seismic cycle in the coming decade of seismic deformation research.

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