Bulletin of the Seismological Society of America, Vol. 99, No. 2B, pp. 945–957, May 2009, doi: 10.1785/0120080344

Introduction to the Special Issue on Rotational Seismology and Engineering Applications

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Abstract Rotational seismology is an emerging field for studying all aspects of rotational ground motions induced by earthquakes, explosions, and ambient vibrations. It is of interest to a wide range of geophysical disciplines, including strong-motion seismology, broadband seismology, earthquake engineering, earthquake physics, seismic instrumentation, seismic hazards, seismotectonics, and geodesy, as well as to physicists using Earth-based observatories for detecting gravitational waves generated by astronomical sources (predicted by Einstein in 1916). In this introduction to the *BSSA* special issue on rotational seismology and engineering applications, we will include (1) some background information, (2) a summary of the recent events that led to this special issue, and (3) an overview of its 51 papers—27 articles, 11 short notes, 4 reviews, 6 tutorials, and 3 supplementary articles. Our comments on these 51 papers are very brief and give just a hint of what the papers are about.

Papers in this special issue demonstrate that earthquake monitoring cannot be limited to measuring only the three components of translational motion. We also need to simultaneously measure the three components of rotational motion and the many components of strains. A golden opportunity to improve our understanding of earthquakes lies in the near field of large earthquakes (within about 25 km of the earthquake ruptures), where nonlinear rock and soil response influences ground motions in a complicated way.

Some Background Information

Rotational effects of earthquake waves together with rotations caused by soil–structure interaction (e.g., in chimneys, monuments, or tombstones rotated on their supports) have been observed for centuries. A few early authors proposed rotational waves or at least some vortical motions. Some of these early observations, however, might have resulted from ground rocking caused by soil–structure interaction. Some early seismic instruments designed to detect and to record earthquake shaking also included the rocking of ground motion because it was believed that earthquakes were caused by explosions in the Earth (Trifunac, 2008). As summarized by Ferrari (2006), two models of an electrical seismograph with sliding smoked paper were developed by P. Filippo Cecchi (1822–1887) to record three-component translation motions and also the torsion movements from earthquakes. Although these instruments operated for several years, no rotational motion could be recorded because of low transducer sensitivity.

Mallet (1862) proposed that rotations of a body on the Earth's surface are due to a sequence of different seismic phases emerging under different angles. Reid (1910) studied this phenomenon, which was observed in the 1906 San Francisco earthquake, and pointed out that the observed rotations are too large to be produced by waves of elastic distortion. Such waves "produce very small rotations, whose maximum amount, … is given by the expression $2\pi A/\lambda$, where A is the amplitude and λ the wave-length; with a wave as short as 10,000 feet (3 km) and an amplitude as large as 0.2 of a foot (6 cm), the maximum rotation would only be about 0.25 of a minute of arc, a quantity far too small to be noticeable."

In classical seismology (see, e.g., Båth, 1979, p. 31), the general motion of the particles in a solid body can be divided into three kinds: translation (along the x, y, and z axes), rotation (about the x, y, and z axes), and deformation. However, modern observational seismology is still based mainly on measuring translational motions due to difficulties involved in measuring rotational motions and strains and because of a widespread belief that rotational motions are insignificant (Gutenberg, 1927). Richter (1958, footnote on p. 213) claimed that "Theory indicates, and observation confirms, that such rotations are negligible." Richter did not provide any references, and there were no instruments sensitive enough to measure rotation motions at the level of microradians per second (μrad/sec) at that time.

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However, despite its difficulties, several pioneers in several countries attempted to measure rotational motions induced by earthquakes, starting with Cecchi (1876). Nearly a century ago, Galitzin (1912) suggested using two identical pendulums installed on different sides of the same axis of rotation for separate measurement of rotational and translational motion. This was later implemented, for example, by Kharin and Simonov (1969) in an instrument designed to record strong ground motion. Using an azimuthal array of seismographs, Droste and Teisseyre (1976) derived rotational seismograms of rock bursts from a nearby mine. Inspired by Walter Munk, Farrell (1969) constructed a gyroscopic seismometer (consisting of two counter-rotating, pendulous Nordsieck gyroscopes, permitting separation of tilts from horizontal translational motion) and obtained a static displacement of <1 cm and a tilt of $<5 \times 10^{-7}$ rad at La Jolla, California, during the Borrego Mountain earthquake of 9 April 1968 (magnitude 6.5) at an epicentral distance of 115 km.

The early efforts also included studying explosions. For example, Graizer (1991) recorded tilts and translational motions in the near field of two nuclear explosions using seismological observatory sensors to directly measure point rotations. Nigbor (1994) directly measured rotational and translational ground motions and observed significant amounts of near-field rotational motions near a large explosion using commercial rotational sensors.

Rotations and strains of the ground and of response of structures have been deduced indirectly from accelerometer arrays using methods valid for seismic waves having wavelengths that are long compared to the distances between sensors (e.g., Castellani and Boffi, 1986; Niazi, 1987; Oliveira and Bolt, 1989; Spudich *et al.*, 1995; Bodin *et al.*, 1997; Huang, 2003; Ghayamghamian and Nouri, 2007; Spudich and Fletcher, 2008). The rotational components of ground motion have also been estimated theoretically, using kinematic source models and linear elastodynamic theory of wave propagation in elastic solids (e.g., Bouchon and Aki, 1982; Trifunac, 1982; Lee and Trifunac, 1985, 1987).

In the past decade, rotational motions from teleseismic and small local earthquakes were successfully recorded by sensitive rotational sensors in Japan, Poland, Germany, New Zealand, and Taiwan (e.g., Takeo, 1998; Teisseyre *et al.*, 2003; Igel *et al.*, 2005; Huang *et al.*, 2006; Suryanto *et al.*, 2006; Igel *et al.*, 2007). In particular, the application of Sagnac interferometry allowed a largely improved sensitivity for the detections of rotation (Pancha *et al.*, 2000). The observations in Japan and Taiwan showed that the amplitudes of rotations can be one to two orders of magnitude greater than expected from the classical elasticity theory, as first noted by Takeo (1998). Theoretical work has also suggested that, in granular materials or cracked continua, asymmetries of the stress and strain fields can create rotations in addition to those predicted by the classical elastodynamic theory (Vardoulakis, 1989; Teisseyre and Boratyński, 2003; Harris, 2006; Grekova *et al.*, 2009; Kulesh, 2009). These rotations naturally generate rotational seismic waves and seismic spin and twist solitons (Majewski, 2006).

Ground motions in the near field (within ~25 km of fault ruptures) of major earthquakes (magnitudes ≥ 7), where the discrepancy between observations and theoretical predictions may be the largest, have rarely been recorded. We know only one recent case where rotational motions have been inferred from a seven-element accelerometer array on the Li-Yu-Tan dam, located 6 km north of the northern end of the 1999 Chi-Chi earthquake (M_w 7.6) fault rupture (Huang, 2003).

Recording such ground motions would require extensive seismic instrumentation along some well-chosen active faults and luck. To this end, several seismologists have been advocating such instrumentation, and a current deployment in southwestern Taiwan by their Central Weather Bureau is designed to capture a repeat of the 1906 Meishan earthquake (magnitude 7.1) with both translational and rotational instruments (see Wu *et al.*, 2009). For studies of near-field motions, one may use explosions or induced seismic effects like rockbursts in mines (Zembaty, 2004). However, these sources cannot substitute for major earthquakes that matter most in seismic hazards.

International Working Group on Rotational Seismology

A brief history leading to the formation of the International Working Group on Rotational Seismology (IWGoRS) is given in the Appendix. IWGoRS aims at promoting investigations of rotational motions and their implications and sharing experience, data, software, and results in an open Web-based environment. It consists of volunteers and has no official status. H. Igel and W. H. K. Lee are serving as its co-organizers, and its charter is accessible on the IWGoRS Web site (see the Data and Resources section). The Working Group has a number of active members leading task forces focusing on the organization of workshops and scientific projects, including testing and verifying rotational sensors, making broadband observations with ring-laser systems, and developing a field laboratory for rotational motions. The IWGoRS Web site also contains the presentations and posters from related meetings, and eventually it will provide access to rotational data from many sources and other online resources.

The IWGoRS organized a special session on Rotational Motions in Seismology, convened by H. Igel, W. H. K. Lee, and M. Todorovska during the 2006 American Geophysical Union (AGU) Fall Meeting (Lee, Igel *et al.*, 2007). The goal of this session was to discuss rotational sensors, observations, modeling, theoretical issues, and potential applications of rotational ground motions. A total of 21 articles were submitted for this session, and over 100 people attended the oral session.

The interest in this session demonstrated that rotational motions are of current interest to a wide range of disciplines, including strong-motion seismology, broadband seismology, earthquake engineering, earthquake physics, exploration seismology, seismic instrumentation, seismic hazards, and geodesy—thus confirming the timeliness of IWGoRS. At this meeting, it became apparent that there is a need for longer meetings dedicated specifically to this topic in order to allow sufficient time for investigators from different countries and different fields to discuss the many issues of interest and to draft a research plan. This led to a plan to hold periodic workshops, the first one to be held in the United States and the next one in Europe.

First International Workshop on Rotational Seismology and Engineering Applications

The First International Workshop on Rotational Seismology and Engineering Applications was held in Menlo Park, California, on 18–19 September 2007. The workshop was hosted by the U.S. Geological Survey (USGS), which recognized this topic as a new research frontier enabling better understanding of earthquake processes and as a more effective approach to reducing seismic hazards.

The technical program consisted of three sessions: plenary and oral, which were held on the first day, and poster, which was held on the second day, followed by discussions. A postworkshop session was held the following day in which scientists of the Laser Interferometer Gravitational-Wave Observatory (LIGO) presented their work on seismic isolation of their ultra-high-precision facility, which requires very accurate recording of translational and rotational components of ground motions.

The workshop began with the plenary session, held on the morning of 18 September at the USGS campus, during which three lectures were presented for the general audience. W. H. K. Lee of the USGS summarized recent observations of rotational ground motions from regional and local earthquakes in Taiwan. M. D. Trifunac of the University of Southern California then spoke on rotations in structural responses, and H. Igel of the University of Munich presented observations of rotational ground motions of earthquakes in the far field using ring-laser gyros. About 100 people attended this session.

The workshop then moved to the nearby Vallombrosa Center for in-depth presentations and discussions among 63 participants, and five oral presentations were given in the afternoon on major areas of research on rotational seismology and engineering issues. The morning session of the following day, 19 September, was devoted to 30 posters covering a wide range of topics, including large block rotations in geological time scale, rotations of monuments after earthquakes, and theories, instruments, observations, and analyses of rotational motions.

In the early afternoon of 19 September, participants were divided into five panels for in-depth discussions, as follows (chairs are listed in parenthesis): (1) theory (L. Knopoff), (2) far field (H. Igel), (3) near field (T. L. Teng), (4) engineering applications (M. Trifunac), and (5) instrument design and testing (J. R. Evans). This was followed by a general discussion in which the panel chairs summarized the group discussions on the key issues and future research directions. It was concluded that collaborative work is essential for nurturing this new field of inquiry and that there are many opportunities for collaborative work across institutions, nations, and disciplines. The panel reports, and the proposed future directions and research plans are described in detail in Lee, Çelebi *et al.* (2007), and the accompanying workshop DVD contains all of the presentation files and supporting materials.

In recognizing this emerging new field, the Seismological Society of America approved on 31 August 2007 the publication of this special issue, and a call for papers was announced in October 2007, inviting open manuscript submission by 31 May 2008.

Contents of the Special Issue

There are three main sections to this issue: (1) introduction and reviews, (2) articles, and (3) short notes. Tutorials and supplementary articles are added to section (1) to help readers become acquainted with this new field.

Reviews

Four reviews are included in this special issue:

1. "*Review*: Progress in Rotational Ground-Motion Observations from Explosions and Local Earthquakes in Taiwan," by W. H. K. Lee, B.-S. Huang, C. A. Langston, C.-J. Lin, C.-C. Liu, T.-C. Shin, T.-L. Teng, and C.-F. Wu.
2. "*Review*: Rotations in Structural Response," by M. D. Trifunac.
3. "*Review*: Requirements for a Ground Rotation Sensor to Improve Advanced LIGO," by B. Lantz, R. Schofield, B. O'Reilly, D. E. Clark, and D. DeBra.
4. "*Review*: Accelerometer Development for Use in Gravitational Wave-Detection Interferometers," by R. DeSalvo.

The first review by Lee *et al.* (2009) is a progress report on observing rotational and translational ground motion from explosions and earthquakes in Taiwan, and it is based on the work by Lin *et al.* (2009), Liu *et al.* (2009), Wu *et al.* (2009), and Langston *et al.*, (2009). Taiwan is at present the only country that has a program for monitoring regional and local earthquakes by both translational and rotational seismometers at several station sites. The second review, by Trifunac (2009b), discusses the rotations in structural response. It argues that recording the rotational components of motion will contribute significantly to information on structural response and recommends development and deployment of instruments to measure rotational components of motion in free-field conditions and full-scale structures.

The third and fourth reviews are included for the benefit of seismologists and earthquake engineers. Nearly a century ago, Einstein (1916) published his theory of General Relativity to describe how the acceleration of massive objects would generate distortions in space–time, resulting in gravitational waves, which propagate at the speed of light. Since then, detecting gravitational waves has been one of the major challenges in modern physics, but direct detection has not yet been achieved. Several major projects have been underway on Earth and in outer space. Lantz *et al.* (2009) review the requirements needed for the construction of the LIGO project—a high-performance seismic isolation and alignment system on which the optical component of the new LIGO detectors will be mounted. DeSalvo (2009) reviews the accelerometer development for use in gravitational-wave-detection interferometers in general. Because the accelerometer is one of the most important transducers for measuring strong ground motions in earthquake engineering and seismology, we can all benefit and learn from this research and development work.

Tutorials

Six tutorials are included in this special issue:

1. "Tutorial on Earthquake Rotational Effects: Historical Examples," by J. T. Kozák.
2. "Tutorial on Rotations in the Theories of Finite Deformation and Micropolar (Cosserat) Elasticity," by J. Pujol.
3. "Tutorial on New Development in the Physics of Rotational Motions," by R. Teisseyre.
4. "Tutorial on Surface Rotations from Wave Passage Effects: Stochastic Spectral Approach," by Z. Zembaty.
5. "Tutorial on Gravitational Pendulum Theory Applied to Seismic Sensing of Translation and Rotation," by R. D. Peters.
6. "Tutorial on Measuring Rotations Using Multipendulum Systems," by V. Graizer.

Because rotational seismology is an emerging field, the guest editors felt that these tutorials would be helpful in providing general background and information. The first tutorial is a summary of historical examples of observations on earthquake rotational effects by Kozák (2009), including reproduction of the relevant sections from Mallet (1862) and Reid (1910).

The next three tutorials address some mathematical and physical aspects of rotational motion. Pujol's (2009) tutorial considers rotations from two approaches: the classical nonlinear theory and a nonclassical linear theory. It discusses the pioneering work of Cosserat and Cosserat (1909) and its subsequent developments (e.g., Eringen, 1999). Teisseyre (2009) highlights new developments in the physics of rotational motions, which are topics for two recently published monographs (Teisseyre *et al.*, 2006, 2008). A short tutorial by Zembaty (2009a) considers a stochastic approach for estimating rotational components of ground motion at the surface due to wave passage.

Because pendulums are central to the design of seismometers, a tutorial on gravitational pendulum theory applied to seismic sensing of translation and rotation is provided by Peters (2009). This is followed by a tutorial by Graizer (2009a) on using a combination of pendulums to measure rotations.

Supplements

The following supplements are included for the convenience of the readers:

1. "Suggested Notation Conventions for Rotational Seismology," by J. R. Evans and International Working Group on Rotational Seismology.
2. "Suggested Readings in Continuum Mechanics and Earthquake Seismology," by E. F. Grekova and W. H. K. Lee, compilers.
3. "A Glossary for Rotational Seismology," by W. H. K. Lee, compiler.

In an effort to unify notation conventions for rotational seismology, Evans circulated an early version of "Suggested Notation Conventions for Rotational Seismology" to members of the IWGoRS. The version published here is based on their input (Evans and IWGoRS, 2009).

Because some readers may not be familiar with modern developments in continuum mechanics (including elasticity theories), Grekova and Lee (2009) compiled suggested readings that may be useful in providing mathematical and physical bases for rotational seismology. They have also included some suggested readings in earthquake seismology for scientists who are not seismologists.

Because standard dictionaries may not include new technical terms, Lee (2009) compiled a list of glossary terms for rotational seismology from contributions of some of the authors of this special issue and also included some glossary terms on earthquakes from Aki and Lee (2003) and Lee and Wu (2009) for the benefit of scientists who are not seismologists.

Because the three supplements are preliminary and updates will be desirable, they will posted online at the IWGoRS Web site (see the Data and Resources section).

Articles and Short Notes

The articles and short notes in this special issue present original research results. For an overview of the contents, we grouped them by subject areas as follows (please note that an article is indicated by a "**" symbol at the end of each entry).

Theoretical Investigations and Simulations.

1. "Single-Couple Component of Far-Field Radiation from Dynamical Fractures," by L. Knopoff and Y.-T. Chen.**
2. "An Asymmetric Micropolar Moment Tensor Derived from a Discrete-Block Model for a Rotating Granular Substructure," by R. J. Twiss.**
3. "Fundamental Deformations in Asymmetric Continuum," by R. Teisseyre and M. Górski.**

4. "Spinors and Twistors in the Description of Rotational Seismic Waves and Spin and Twist Solitons," by E. Majewski.**
5. "Waves in Linear Elastic Media with Microrotations, Part 1: Isotropic Full Cosserat Model," by M. Kulesh.
6. "Waves in Linear Elastic Media with Microrotations, Part 2: Isotropic Reduced Cosserat Model," by E. F. Grekova, M. A. Kulesh, and G. C. Herman.
7. "Rotational Motions of Seismic Surface Waves in a Laterally Heterogeneous Earth," by A. M. G. Ferreira and H. Igel.
8. "Numerical Simulation of Ground Rotations along 2D Topographical Profiles under the Incidence of Elastic Plane Waves," by L. Godinho, P. A. Mendes, A. Tadeu, A. Cadena-Isaza, C. Smerzini, F. J. Sánchez-Sesma, R. Madec, and D. Komatitsch.**
9. "Source and Basin Effects on Rotational Ground Motions: Comparison with Translations," by H. Wang, H. Igel, F. Gallovič, and A. Cochard.**

Unlike the traditional fault-slip model, the article by Knopoff and Chen (2009) considers the case for faulting that takes place on a fault of finite thickness. They show that there is an additional single-couple term in the body-force equivalence and additional terms in the far-field displacement. They also show that the single-couple equivalent does not violate the principles of Newtonian mechanics, because the torque imbalance in the single-couple is counterbalanced by rotations within the fault zone, with torque waves being radiated.

In the article by Twiss (2009), an asymmetric moment tensor for individual and averaged multiple slip events is introduced. Three field tests of the theory are described. The author points out, however, that a definitive test is difficult due to insufficient quantitative information and a lack of resolution.

Teisseyre and Górski (2009) investigate a class of basic motions and deformations in an asymmetric continuum that includes not only simple motions like translation and rotation but also point extension/compression (axial deformation) and point string deformation with extension and compression acting simultaneously at the perpendicular orientation. Majewski (2009) applies the theory of spinors and twistors to describe spin and twist solitons branching off dispersion curves for rotational seismic waves. A nonlinear Schrödinger equation is proposed to describe seismic twist waves and solitons.

The two short notes by Kulesh (2009) and by Grekova *et al.* (2009) investigate the consequences of a Cosserat continuum on the problem of wave propagation. In an isotropic full Cosserat model, Kulesh (2009) finds that Rayleigh and transverse surface waves are dispersive in a half-space. Grekova *et al.* (2009) investigate the reduced Cosserat model in which translations and rotations are kinematically independent, but the couple stress tensor is zero. Strongly dispersive behavior is predicted.

The following articles in this subsection investigate rotational motions from a theoretical point of view but within the theory of linear elasticity. Ferreira and Igel (2009) employ generalized ray theory to calculate synthetic Love-wave seismograms for 3D heterogeneous Earth models. They show that the amplitude ratios of translational and rotational signals are sensitive to local velocity structure and that in theory the spectral ratios are proportional to Love-wave dispersion curves. Godinho *et al.* (2009) use the method of fundamental solutions to investigate the effects of 2D surface topography on rotational ground motions, verify their results by comparing them with other numerical solutions, and discuss the effects in both frequency and time domains.

Finally, Wang *et al.* (2009) use a database of precalculated numerical Green's functions of a simplified model of the Newport-Inglewood fault, Los Angeles Basin, to synthesize translational and rotational ground motions of several M 7 earthquakes in a 3D basin structure. They discuss peak ground-motion characteristics and conclude that the decay of rotation rate as a function of fault distance is similar to that of horizontal accelerations.

Instrumentation and Testing.

1. "Research and Development Status of a New Rotational Seismometer Based on the Flux Pinning Effect of a Superconductor," by A. Takamori, A. Araya, Y. Otake, K. Ishidoshiro, and M. Ando.**
2. "Performance Characteristics of a Rotational Seismometer for Near-Field and Engineering Applications," by R. Cowsik, T. Madziwa-Nussinov, K. Wagoner, D. Wiens, and M. Wysession.**
3. "Ring Laser Measurements of Ground Rotation for Seismology," by K. U. Schreiber, J. N. Hautmann, A. Velikoseltsev, J. Wassermann, H. Igel, J. Otero, F. Vernon, and J.-P. R. Wells.**
4. "Perspectives for Ring Laser Gyroscopes in Low-Frequency Seismology," by R. Widmer-Schnidrig and W. Zürn.**
5. "The Application of Fiber Optic Gyroscopes for the Measurement of Rotations in Structural Engineering," by K. U. Schreiber, A. Velikoseltsev, A. J. Carr, and R. Franco-Anaya.**
6. Design of a Relatively Inexpensive Ring Laser Seismic Detector," by R. W. Dunn, H. H. Mahdi, and H. J. Al-Shukri.
7. "Strong-Motion Fluid Rotation Seismograph," by P. Jedlička, J. Buben, and J. Kozák.
8. "Laboratory and Field Testing of Commercial Rotational Seismometers," by R. L. Nigbor, J. R. Evans, and C. R. Hutt.**
9. Performance Test of a Commercial Rotational Motions Sensor," by J. Wassermann, S. Lehndorfer, H. Igel, and U. Schreiber.

Takamori *et al.* (2009) report on the development of a seismometer with a new design based on a proof mass levitated by a magnetic suspension that uses the flux pinning effect of a superconductor. Prototype systems were built and tested to assess the feasibility of the technologies, as well as their advantages and capabilities. The design of the new seismometer, together with the status of the development and future plans, are presented in this article. Cowsik *et al.* (2009) developed a prototype of a rotation sensor using a torsional balance. They present the preliminary data recorded with this instrument and discuss the instrument's sensitivity and suitability for extended seismological studies.

Schreiber, Hautmann, *et al.* (2009) describe a ring-laser system (called a Geosensor) that was specifically designed to fulfill the needs of broadband seismology. A prototype of this sensor was installed at the Piáon Flat Observatory in Southern California, and data examples are presented. Widmer-Schnidrig and Zürn (2009) look at the perspectives of ring-laser measurements for long-period seismology. They quantify the contribution of ring-laser tilting and investigate noise levels and current instrument resolution. They conclude that at present the amplitudes of eigenvibrations are below the detection threshold.

Schreiber, Velikoseltsev, *et al.* (2009) report on the design of, and laboratory and field experiments with, a rotation sensor based on fiber-optic gyro (FOG) technology. Such FOGs are exploiting the Sagnac effect in a passive optical interferometer in order to measure rotations with high precision. For that reason, these FOGs can measure rotations absolutely and do not require a specific frame of reference. Dunn *et al.* (2009) examine design options for deploying a relatively low-cost ring-laser ground-rotation sensor and conclude with a discussion of some earthquakes detected by such an instrument. Jedlička *et al.* (2009) report on a new type of fluid, ring-shaped, rotational seismometer in which the inertial mass is represented by a liquid moving in a ring tube.

Nigbor *et al.* (2009) develop performance test methodologies for rotational seismometers and apply these methodologies to samples of a commonly used commercial rotational seismometer, the eentec model R-1 (see the Data and Resources section for more information). Wassermann *et al.* (2009) compare recordings of the collapse of a large building with the R-1 rotation seismometer with rotational motions derived from an array of translational sensors around the R-1. For some components of rotation, a fairly good fit in waveform and amplitude is observed between direct and array-derived measurements.

Observations of Translational and Rotational Ground Motion.

1. "Observing Rotational and Translational Ground Motions at the HGSD Station in Taiwan from 2007 to 2008," by C.-C. Liu, B.-S. Huang, W. H. K. Lee, and C.-J. Lin.**
2. "Recording Rotational and Translational Ground Motions of Two TAIGER Explosions in Northeastern Taiwan on 4 March 2008," by C.-J. Lin, C.-C. Liu, and W. H. K. Lee.**
3. "Rotational Motions Observed during an Earthquake Swarm in April 1998 Offshore Ito, Japan," by M. Takeo.
4. "Array Deployment to Observe Rotational and Translational Ground Motions along the Meishan Fault, Taiwan: A Progress Report," by C.-F. Wu, W. H. K. Lee, and H.-C. Huang.
5. "Rotational Earthquake Effects in the United Kingdom," by S. L. Sargeant and R. M. W. Musson.

The article by Liu *et al.* (2009) reports on the deployment of rotation seismometers (R-1 by eentec) at the HGSD station in Taiwan starting in 2004 and about the rotational ground-motion observations from a few hundred local earthquakes. Their data from colocated translational accelerometer and rotational seismometer suggest that there is a linear relationship between peak ground acceleration and peak ground rotational velocity. Two explosions in northeastern Taiwan were recorded with rotation and translation sensors in a 12-station array close to the source. Lin *et al.* (2009) present details on the experiment, show the observation data, and will release the data for open access.

Takeo (2009) observes six components of ground rotational and translational motions in a near-field region during an earthquake swarm in April 1998, offshore of Ito, Izu Peninsula, Japan. The observed rotational motions are comparatively larger than those calculated by array data at the San Andreas fault. Possible causes are discussed.

Wu *et al.* (2009) report on the deployment of two local seismic arrays (one in the free field and the other in a nearby building) at the 1906 ruptured zone of the Meishan fault, Taiwan. These arrays include accelerometers and rotational seismometers and are designed for capturing strong ground motions from an anticipated major earthquake. The experimental setup is described, and the data recorded with the rotational seismometer are presented and compared with the translational data. Sargeant and Musson (2009) describe a number of instances in the United Kingdom of earthquake-induced rotational effects on parts of structures, mostly either chimneys or the tops of spires. They assembled all of the instances and present them with illustrations and extracts from the original reports.

Analysis of Translational and Rotational Ground Motion.

1. "Tilt Motions Recorded at Two WISE Sites for the 2003 Tokachi-Oki Earthquake (*M* 8.3)," by S. Kinoshita, H. Ishikawa, and T. Satoh.**
2. "The Effect of Torsional Ground Motion on Structural Response: Code Recommendation for Accidental Eccentricity," by M. R. Ghayamghamian, G. R. Nouri, H. Igel, and T. Tobita.**
3. "Study of Rotational Ground Motion in the Near-Field Region," by M. Stupazzini, J. de la Puente, C. Smerzini, M. Käser, H. Igel, and A. Castellani.**

4. "Seismic-Wave Strain, Rotation, and Gradiometry for the 4 March 2008 TAIGER Explosions," by C. A. Langston, W. H. K. Lee, C. J. Lin, and C. C. Liu.**
5. "Sensitivity Densities for Rotational Ground-Motion Measurements," by A. Fichtner, and H. Igel,**
6. "Observations and Modeling of Rotational Signals in the *P* Coda: Constraints on Crustal Scattering," by N. D. Pham, H. Igel, J. Wassermann, M. Käser, J. de la Puente, and U. Schreiber.**
7. "Interpretation of Broadband Ocean-Bottom Seismometer Horizontal Data Seismic Background Noise," by R. Pillet, A. Deschamps, D. Legrand, J. Virieux, N. Béthoux, and B. Yates.**
8. "About the Nonunique Sensitivity of Pendulum Seismometers to Translational, Angular, and Centripetal Acceleration," by T. Forbriger.**
9. "The Effects of Tilt on Interferometric Rotation Sensors," by N. D. Pham, H. Igel, J. Wassermann, A. Cochard, and U. Schreiber.**
10. "The Response to Complex Ground Motions of Seismometers with Galperin Sensor Configuration," by V. Graizer.**
11. "Software for Inference of Dynamic Ground Strains and Rotations and Their Errors from Short Baseline Array Observations of Ground Motions," by P. Spudich and J. B. Fletcher.

Kinoshita *et al.* (2009) analyze tilt motions recorded during the M 8.0 Tokachi-Oki earthquake in 2003 by broadband velocity seismographs. They conclude that the long-period tilt signal was produced by collapsed soil structure or the deformation of the soil deposits. They also conclude that velocity seismographs are more sensitive to tilt motion than accelerographs. Ghayamghamian *et al.* (2009) use data from the Chiba dense array in Japan to compute torsional time histories, which they use as input motion for symmetric and asymmetric one-story buildings. They show that the rotations can increase the response of the structure.

Stupazzini *et al.* (2009) perform high-resolution numerical calculations of ground motions for a 3D model of the Grenoble Valley, France. They investigate peak ground translations and rotations and find that their ratio correlates with the local velocity structure. Langston *et al.* (2009) analyze the data recorded after the TAIGER explosions (see also Lin *et al.*, 2009) using array-processing techniques, and they derive strain and rotation from the array data and interpret the results in terms of scattering or source characteristics.

Fichtner and Igel (2009) use the adjoint technique to derive sensitivity kernels for a newly defined observable—apparent shear velocity—that can be derived from colocated measurements of translations and rotations. They show that high sensitivity is concentrated around the receiver, which supports the observation that the ratio of translations and rotations contains information about near-surface structure. Pham, Igel, Wassermann, Käser, *et al.* (2009) report on observations of rotational ground motions with the P-code of teleseismic signals. It is concluded that near-receiver *P-SH* scattering is the primary cause of these signals. Using 3D numerical simulations, they are capable of constraining the scattering properties of the near-receiver crustal structure.

The problem of noise on the sea floor recorded by broadband seismic sensors is investigated by Pillet *et al.* (2009), who show that rotational motions are likely to generate a substantial part of the noise and argue that rotational motions should be recorded at the sea floor in order to reduce these effects and improve the signal-to-noise ratio. Forbriger (2009) investigates the sensitivity of pendulum instruments to various types of rotational motions. He concludes that a pendulum seismometer appears sensitive to linear acceleration only if the output signal is referred to the motion of the point mass of the equivalent simple pendulum.

Pham, Igel, Wassermann, Cochard, and Schreiber (2009) investigate cross-axis sensitivity of ring-laser systems theoretically. They quantify the effects of tilt motions on the observations of rotational motions around a vertical axis to be expected in the *P* coda of several past earthquakes. The results show that the effects of tilts on ring-laser measurements are negligible not only for observations of teleseismic events but also for the applicable range of the local magnitude scale.

The article by Graizer (2009b) considers the response to input motions of pendulums in a Galperin sensor configuration as well as the resulting cardinal orientation system response, and the author concludes that this geometry might also be useful for strong-motion applications.

Spudich and Fletcher (2009) derive expressions for the error covariance matrices of strains and rotations inferred from seismic array data. They present MATLAB scripts (freely available online as a *BSSA* electronic supplement) for the calculation of ground strains, rotations, and their variances from short-baseline-array ground-motion data.

Engineering Applications.

1. "Empirical Scaling of Rotational Spectra of Strong Earthquake Ground Motion," by V. W. Lee and M. D. Trifunac.**
2. "Transient and Permanent Rotations in a Shear Layer Excited by Strong Earthquake Pulses," by V. Gičev and M. D. Trifunac.**
3. "Response Spectra for Near-Source, Differential, and Rotational Strong Ground Motion," by R. S. Jalali and M. D. Trifunac.**
4. "Rotational Seismic Load Definition in Eurocode 8, Part 6, for Slender, Tower-Shaped Structures," by Z. Zembaty.

Lee and Trifunac (2009) present a simple approximate algorithm for generation of torsional and rocking Fourier spectra from Fourier spectra of translational motions, predicted empirically or recorded. These spectra can be used consequently to generate torsional and rocking time histories. Gičev and Trifunac (2009) study rotational waves in a nonlinear (bi-linear) soil layer generated by vertically arriving *S*-wave pulses of strong ground motion. The complexity of the soil layer response revealed by this simple nonlinear model provides a glimpse into the complexity of a realistic setting.

Jalali and Trifunac (2009) analyze the pseudorelative spectral velocity (PSV) of an equivalent oscillator representing a structure, excited by simultaneous action of horizontal, vertical, and rocking components of strong ground motion. Their results show that, at long periods, the PSV spectral amplitudes tend toward an asymptote with amplitude proportional to the maximum rocking angle of ground motion. Zembaty (2009b) describes the rotational seismic load provisions in the European seismic code EC8.6 for towers, masts, and chimneys, and he concludes that the engineering code formulas should be calibrated and reconciled with the results of the latest empirical research on the rocking component of ground motion.

Discussion

This special issue is a result of the First International Workshop on Rotational Seismology and Engineering Applications, and we repeat here several recommendations that emerged from the workshop. In addition, we discuss briefly the role of rotational seismology in the strong-motion programs, rotational motions and seismic wave propagation, and classical elasticity versus other theories.

Recommendations from the 2007 Workshop

1. Because the classical linear-elasticity theory may be inadequate, a more realistic theory should be developed, especially for rotational motions in the near field.
2. Using existing data and collecting more data from existing rotational instruments, one or more rotational-motion noise models (e.g., low noise, high noise) should be established. These noise models should be updated as more data become available.
3. Three-component ground rotations should be recorded (using commercially available rotation sensors) at seismological stations that operate near active seismic zones. At first, this should be done at perhaps a dozen stations, on a trial basis, to collect sufficient rotational motion data upon which future deployments can be based.
4. Large-ring lasers (at least one component, preferably three components) should be installed and operated at several high-quality seismological observatories. For those interested in tilt signals (LIGO, USGS/Albuquerque Seismological Laboratory [ASL]), comparing rotation about one or both horizontal axes to the output of high-quality, very-broadband horizontal instruments, like the STS-1H/VBB seismometer, will be important.
5. Rotational motion should be recorded in selected structures and at depth below them, especially for structures in active seismic zones.
6. Development of high-quality, low-cost rotational seismometers should be encouraged. This will require research and development funding because the market for rotational seismometers is currently small.
7. Techniques and facilities should be developed for rotational sensor testing.
8. Funding agencies should be urged to support: (a) deployment of rotational sensors on the ground and in structures and (b) research involving the rotational components of ground motion and of the response of structures.

We are pleased to note that some of the previous recommendations have already been carried out, as reported in this special issue, which contains the results of about 100 authors from diverse backgrounds, including seismologists, earthquake engineers, physicists, astrophysicists, geologists, and mathematicians.

Rotational Seismology and Strong-Motion Programs

Until recently, earthquake monitoring in the near field has been left to the earthquake engineers. In his account of early earthquake engineering, Housner (2002) credited John R. Freeman, an eminent engineer, for persuading the U.S. government to start a strong-motion program. In a letter to R. R. Martel (Housner's professor) at Caltech, Freeman wrote, “I stated that the data which had been given to structural engineers on acceleration and limits of motion in earthquakes as a basis for their designs were all based on guesswork, that there had never yet been a precise measurement of acceleration made. That of the five seismographs around San Francisco Bay which tried to record the earthquake of 1906 not one was able to tell the truth.”

Subsequently, the U.S. government provided funding for the design of an accelerograph for engineering purposes in 1930 and for deployment of some dozen strong-motion accelerographs (Trifunac, 2008).

Strong-motion recordings useful for engineering purposes are on-scale recordings of damaging earthquakes. The strong-motion data collected from the 1999 Chi-Chi, Taiwan, earthquake (M_w 7.6) are thus far the best example of how useful large-scale deployment of strong-motion instruments can be (Lee *et al.*, 2001; Lee, 2002). Having an $M \geq 7$ earthquake occurring near seismic stations is rare. According to Norm Abrahamson (personal comm., 2000), designs of large engineering structures benefit most from strong-motion records of $M \geq 7$ earthquakes obtained within 20 km of fault ruptures. As of mid-1999, there were only eight such strong-motion records in the world after nearly 70 yr of effort in strong-motion monitoring. The Kocaeli, Turkey, earthquake of 17 August 1999 contributed five such records, and the Chi-Chi, Taiwan, earthquake of 20 September 1999 contributed over 60 such records, thanks to the deployment of over 1000 strong-motion instruments 3 yr earlier.

However, there are difficulties in obtaining accurate displacement from the near-field records, and several authors have shown that acceleration recorded by translational sensors must be corrected for the effects of rotational motions (e.g., Trifunac and Todorovska, 2001; Graizer, 2005).

Rotational Motions and Seismic-Wave Propagation

Although rotational motions are interesting phenomena in their own right, they actually represent a way of integrating several basic seismological concepts and instrumentation programs into a coherent framework that can be used to characterize seismic-wave propagation from a wave point of view as opposed to our standard way of examining translational particle motions (C. A. Langston, personal comm., 2008).

A seismic wave is not only a temporal disturbance but a spatial one as well. Seismic rotations and strains are composed of spatial gradients that, through compatibility relationships with the original wave field, can be used to determine many more attributes of a seismic wave from point measurements than we commonly use today. Linking observational translations, strains, and rotations together can yield a snapshot of the wave field where wave direction, slownesses, and radial/azimuthal amplitude gradients can be directly inferred from the data (Langston, 2007; Langston and Liang, 2008). Dense spatial mapping of these wave characteristics through strain and rotational gradiometry (or by the Seismogeodetic method of Spudich *et al.* [1995] and Spudich and Fletcher [2008]) might offer an order-of-magnitude increase in the number of constraints available for studies of velocity heterogeneity (tomography, wave scattering, and anisotropy), source complexity (rupture propagation and finiteness), and media nonlinearity in strong ground motions. It can also lead to new ways of seismic-wave recording where point arrays can be made to determine wave properties through joint recordings of rotation, strain, and translation (Aldridge *et al.*, 2006).

Classical Elasticity versus Other Theories

The real materials of the Earth are heterogeneous and anisotropic, and nonlinear processes are important, especially in the damage zone surrounding faults and in the sediments and soil near the seismic sensors. In the presence of large nonlinearities, we are forced to consider the mechanics of chaos (Trifunac, 2009a), and in order to interpret such complexities we must record also the rotational components of strong motion.

L. Knopoff (personal comm., 2008) thinks that from a theoretical point of view, rotational motions are an essential (unavoidable) component of linear S-wave seismology even for elastic media where rotations are expressed via the curl of translational motions (Bullen, 1953). Y. T. Chen (personal comm., 2008) suggests that in principle the Knopoff and Chen (2009) results can be extended into the inhomogeneous, anisotropic case and full wave field as in Burridge and Knopoff (1964) for exploring the additional effects due to material asymmetry and in the near field.

According to R. Teisseyre (personal comm., 2008), the classical seismology has still enough tools to trace the rotational motions at least around the vertical axis: an array of the horizontal seismometers can deliver the data from which the rotational motions can be derived. However, such a system cannot trace the independent rotations and shear strain variations (twist motions) when generated in source with some phase delay. Thus, the rotational seismology with the use of strainmeters or rotation seismographs may bring much more information on the source-generated processes.

Modern continuum mechanics have advanced far beyond the classical elastic continuum in the past century. The Cosserat theory is of particular interest to rotational seismology because it includes rotation in its formulation; see, for example, the tutorial by Pujol (2009) and the two articles by Kulesh (2009) and Grekova *et al.* (2009). Other general continua, such as asymmetric continuum, are discussed by Teisseyre and Górski (2009) also.

Conclusion

Seismology has been very successful in the far field because large earthquakes occur every month somewhere on Earth and the classical elasticity theory works very well for interpreting the recorded translational motions. Consequently, most funding for earthquake monitoring goes into global and regional seismic networks using exclusively translational seismometers. However, to understand strong ground motions we must deploy appropriate instruments in the near field of active faults where large earthquakes ($M > 6.5$) occur infrequently. This is a risky business because the recurrence of a large earthquake at a given fault may not take place for hundreds of years—many times longer than the carrier span of any scientist. Like astronomers, seismologists must accumulate data over centuries and must be willing to invest to observe earthquakes in the near field.

At present, only Taiwan has a modest program to monitor both translational and rotational ground motions from local and regional earthquakes at several free-field sites, as well as two arrays equipped with both accelerometers and rotational seismometers (one in a building and the other at a free-field site nearby). The R-1 rotational seismometer from eentec produces useful data (see Lin *et al.*, 2009; Liu *et al.*, 2009; Wu *et al.*, 2009), but we must continue to develop reliable and less-expensive rotational seismometers for extensive field deployment. Five articles in this special issue (Cowsik *et al.*, 2009; Dunn *et al.*, 2009; Jedlička *et al.*, 2009; Schreiber, Hautmann, *et al.*, 2009; Takamori *et al.*, 2009) describe new instrument developments.

It took about 40 yr from the time Biot (1934) formulated the concept of the response spectrum until the method was finally adopted by engineers in the design of earthquake-resistant structures (Trifunac, 2007). We may also recall that it took many years to overcome the initial skepticism about relativity theory and quantum mechanics in the early twentieth century. However, based on the developments described here, we believe that observation and analysis of rotational ground motion will soon play a significant role in the next-generation advances in seismology and earthquake engineering. Many authors have already emphasized the benefits of studying rotational motions—see, for example, Twiss *et al.* (1993), Takeo and Ito (1997), and Teisseyre *et al.* (2006).

The study of earthquakes cannot be limited to measuring only the three components of translational motion. We also need to simultaneously measure the three components of rotational motion and the many components of strains (6 components in the classical continuum, or 9 components in the reduced Cosserat medium, or 18 independent measures of strain in the complete Cosserat medium). A golden opportunity to improve our understanding of earthquakes lies in the near field of major earthquakes (within about 25 km of the earthquake ruptures), where nonlinear rock and soil response influences ground motions in a complicated way.

So far, nearly all of the investigations of rotational motions have been carried out without any significant funding support. We hope that the articles in this special issue will create more interest in rotational seismology and, hopefully, more funding in the near future. More importantly, we need help from experts of different disciplines to solve many scientific and technical problems in the near field of major earthquakes. As a reader of this special issue, are you ready for this challenge?

Data and Resources

No data were used in this article. For more information on IWGoRS, see http://www.rotational-seismology.org/. For more information on the eentec Model R-1, see http://www.eentec.com/.

Acknowledgments

We wish to acknowledge the partial financial support from the USGS for publication of this *BSSA* special issue. In particular, we wish to thank David Applegate, Mike Carr, Rufus Catchings, and Bill Leith of the USGS for their encouragement and support. Small partial support was also provided by National Science Foundation Grant Number CMMI-0712053.

We thank Andrew J. Michael, the Editor, and Carol A. Mark, the Managing Editor, for their support and cooperation in producing this issue. We also thank the authors for their dedication to investigate various aspects of rotational seismology and its engineering applications. Special thanks go to reviewers of all the articles presented here: their time, effort, and constructive comments improved the whole of the issue.

We are grateful for corrections, comments, and suggestions by Yun-Tai Chen, John Evans, Andreas Fichtner, Thomas Forbriger, Vladimir Graizer, Elena Grekova, Ken Hudnut, Leon Knopoff, Jan Kozák, Chuck Langston, Brian Lantz, Eugene Majewski, Andy Michael, Bob Nigbor, Nguyen Dinh Pham, Fred Pollitz, Jose Pujol, Ulrich Schreiber, Paul Spudich, Akiteru Takamori, Roman Teisseyre, Mihailo Trifunac, Robert Twiss, Rudolf Widmer-Schnidrig, and Zbigniew Zembaty. We thank Ray Hardesty for his excellent technical editing, courtesy of Mihailo Trifunac.

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Appendix

A Brief History Leading to the Formation of IWGoRS

The Incorporated Research Institutions for Seismology (IRIS) Broadband Seismometer Workshop was held 24–26 March 2004 in Granlibakken, California, to discuss prospects for low-frequency seismometry (Ingate and Berger, 2004). Shortly before this workshop, S. C. Liu, a director of the U.S. National Science Foundation (NSF), asked W. H. K. Lee if a similar NSF sponsored workshop would be desirable for strong-motion instruments. This prompted Lee to search the literature for new instruments (such as Global Positioning Systems [GPS], gyros, jerkmeters, and sensor network) that might be of use for strong-motion seismology and earthquake engineering. Lee contacted some people (e.g., John Evans and Ken Hudnut) and proposed a workshop in 2005. Unfortunately, the reorganization of earthquake engineering program of NSF put this workshop idea to rest.

However, inspired by a talk by Ken Hudnut on integrating real-time GPS with rotational and inertial sensors (Hudnut, 2005) and discussions with many colleagues (including J. R. Evans, V. Graizer, K. W. Hudnut, C. C. Liu, R. Nigbor, and M. D. Trifunac), a Mini-Workshop on Rotational Seismology was organized by Lee (with Hudnut and Evans as coordinators) on 16 February 2006. It was held simultaneously at the USGS offices at Menlo Park and Pasadena, California, with about 30 participants from about a dozen institutions participating via teleconferencing and telephone (Evans *et al.*, 2007).

No funding was available for this mini-workshop, and Lee was impressed by the enthusiastic participation of about a dozen researchers from diverse disciplines interested in rotational ground motions. After the mini-workshop, Evans and Lee contacted active groups in several countries, for example, Germany and Poland. Thus, the mini-workshop led to the idea of organizing an international working group on rotational seismology (IWGoRS). Heiner Igel proposed and implemented a Web site base working group. Unlike the traditional working group appointed by scientific societies or government agencies, Igel and Lee decided to bypass this tradition so that anyone can join IWGoRS.

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Manuscript received 1 December 2008