ROTATIONAL EARTHQUAKE MOTIONS – INTERNATIONAL WORKING GROUP AND ITS ACTIVITIES

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ABSTRACT :

The motion of a point is specified completely by its six components: three translations and three rotations. Traditionally, only the translational components of the earthquake ground shaking and structural response have been recorded. In part, the absence of direct observations of rotational motions resulted from lack of inexpensive rotational sensors with sufficient sensitivity to measure small rotations caused by earthquakes. Recently, however, rotations from teleseismic and small local earthquakes were successfully recorded (ring laser gyros, fiber optic gyros, electro-chemical sensors, etc.), in Japan, Poland, Germany, New Zealand, and Taiwan.

This paper introduces the recently formed International Working Group on Rotational Seismology (IWGoRS) and its activities (http://www.rotational-seismology.org). This group aims to promote investigations of rotational motions (of ground and in structures) and their implications, and to facilitate sharing of experience, data, software and results in an open web-based environment. Its activities include publications, organizing professional meetings, and interactions with professional bodies in engineering and science. Anyone who is interested can join IWGoRS, and its website is freely accessible. H. Igel and W.H.K. Lee serve as co-organizers, and M.D. Trifunac leads the task force for strong motion and earthquake engineering. The IWGoRS recently organized the First International Workshop on Rotational Seismology and Engineering Applications, hosted by U.S. Geological Survey in Menlo Park, California, U.S.A., on Sept. 18 - 19, 2007, convened by W.H.K. Lee, M. Celebi and M Todorovska. This meeting was attended by more than 60 participants from 13 countries. The key issues and research directions were reviewed with emphasis on their relevance for earthquake engineering. A special issue of the Bulletin of Seismological Society of America on Rotational Seismology and Engineering Applications is being prepared under the guest editorship of W.H.K. Lee, M. Celebi, M.I. Todorovska, and H. Igel, and is scheduled to appear in May, 2009. It will be dedicated to the emerging field of seismological research on all aspects of rotational ground motions (including theory, instrumentation, observation, and interpretation) from teleseismic and local earthquakes, as well as to rotations in structural response. It will contain original articles, short technical notes, in-depth and up-to-date reviews, and tutorials.

The next workshop will be organized in Europe in 2009 by H. Igel, U. Schreiber and A. Cochard.

This paper summarizes the key issues and future directions in engineering applications of rotational motions identified in group discussions at the First International Workshop on Rotational Seismology and Engineering Applications, and is based on the workshop proceedings.

KEYWORDS: Rotational seismology, rotational strong ground motion, rotational transducers and instrumentation, rotations in structural response.

1. INTRODUCTION

In the absence of direct measurements, the rotations of ground motion and in the response of structures have been deduced indirectly from instrument arrays. However such estimates are valid only for long wavelengths relative to the distances between the recording sensors (Castellani and Boffi, 1986; Niazy 1987; Oliveira and Bolt 1989; Spudich et al. 1995; Huang 2003; Ghayamghamian and Nouri 2007). The rotational components of ground motion have also been estimated theoretically, using kinematic source models and linear elastodynamic theory of wave propagation in soil and in sedimentary layers (Bouchon and Aki 1982; Trifunac 1982; Lee and Trifunac 1985, 1987). The rotations in structural response, and the contributions to the response from the rotational components of the ground motion have also been of interest for many decades (e.g. Newmark 1969; Luco 1976; Rutenberg and Heidebrecht 1985; Gičev and Trifunac 2008). Recent reviews on rotational motions in seismology and on the effects of the rotational components of ground motion on structures can be found, for examples, in Cochard et al. (2006) and Trifunac (2006).

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 and Ito 1997; Takeo 1998; Teisseyre et al. 2003; Igel et al. 2005, 2007; Huang et al. 2006; Suryanto et al. 2006). The observations in Japan and Taiwan showed that the amplitudes of rotations can be one to two orders of magnitude grater than expected from the classical linear theory. Permanent tilts near Pacoima Dam site in California have shown also that ground rotations which accompany nonlinear site response can be orders of magnitude larger than the rotations computed by classical linear wave propagation theory (Trifunac 2008). Theoretical work has further 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 for a perfect continuum (Teisseyre and Boratńyski 2003).

Rotational motions in the near field (within one source dimension of fault rupture) of strong earthquakes (e.g. M >6.5), where the discrepancy between observations and predictions based on extrapolated empirical scaling and on linear wave propagation theory may be the largest, have not been recorded so far. Recording such ground motions will require extensive seismic instrumentation along some well-chosen active faults. To this end, several seismologists and earthquake engineers have been advocating such measurements, and a current modest deployment in southwestern Taiwan by its Central Weather Bureau is designed to “capture” a repeat of the 1906 Meishan earthquake (magnitude 7.1) with both translational and rotational instruments (Wu et al. 2009).

2. INTERNATIONAL WORKING GROUP ON ROTATIONAL SEISMOLOGY (IWGORS)

Various factors, such as the growing number of successful direct measurements of rotational ground motions (e.g. by ring laser gyros, fiber optic gyros, and sensors based on electro-chemical technology), and the rising awareness about the usefulness of the information they provide (e.g., in constraining the earthquake rupture properties, extracting information about subsurface properties, and about deformation of structures during seismic and other excitation), and about the limitations of the information that can be extracted from the translational sensors due to their sensitivity to rotational motions (e.g., computation of permanent displacements from accelerograms (Graizer, 1991, 2005; Trifunac and Todorovska 2001; Boroschek and Legrand 2006)), lead to the interest to organize the scientific community interested in rotational motions.

First, a monograph on Earthquake Source Asymmetry, Structural Media and Rotation Effects was published, edited by Teisseyre, Takeo and Majewski (2006), with contributions from many authors. A small workshop on Rotational Seismology was organized by W.H.K. Lee, K. Hudnut, and J. R. Evans of the USGS on 16 February 2006 in response to this interest. It was held 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). These events further led to the formation of the International Working Group on Rotational Seismology in 2006, inaugurated during the AGU 2006 Fall Meeting in San Francisco.

International Working Group on Rotational Seismology (IWGoRS) aims to promote investigations of rotational motions and their implications, to share 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 at present serving as “co-organizers”. Its charter is accessible on web site (http://www.rotational-seismology.org). 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, broadband observations with ring laser systems, and developing a field laboratory for rotational motions. The IWGoRS web site also contains presentations and posters from related meetings, and eventually will provide access to rotational data from many sources.

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 AGU Fall Meeting (Lee et al. 2007a). A total of 21 papers were submitted for this session, and over 100 individuals attended the oral presentations.

This was followed by the First International Workshop on Rotational Seismology and Engineering Applications, hosted by U.S. Geological Survey in Menlo Park, California, U.S.A., on Sept. 18 - 19, 2007, and convened by W.H.K. Lee, M. Celebi and M Todorovska (Lee et al., 2007b). This meeting was attended by more than 60 participants from 13 countries.

A special issue of the Bulletin of Seismological Society of America on Rotational Seismology and Engineering Applications was approved under the guest editorship of W.H.K. Lee, M. Celebi, M.I. Todorovska, and H. Igel, to appear in May, 2009. The next workshop will be organized in Europe in 2009 by H. Igel, U. Schreiber and A. Cochard.

3. FUTURE DIRECTIONS IN ENGINEERING APPLICATIONS OF ROTATIONAL MOTIONS

Following the technical presentations, the participants of the First International Workshop on Rotational Seismology and Engineering Applications (Sept. 18 - 19, 2007, in Menlo Park, California) were divided in five panels for in-depth discussions: (1) theory, (2) far-field studies, (3) near-field studies, (4) engineering applications, and (5) instrument design and testing. Following these discussions, all participants met again to hear reports from the group leaders and for general discussion of key issues and future research directions. Details about these discussions can be found in the workshop proceedings (Lee et al., 2007b). This paper discusses only the key issues and research directions identified by the Engineering Applications panel, and the recommendations and conclusions, aiming to familiarize the participants of the 14th World Conference on Earthquake Engineering, with the identified research needs in the engineering aspects of strong motion excitation and in the response of full-scale structures. The Engineering Applications panel consisted of: R. Borcherdt, R. Boroschek, G. Brady, A. Cadena-Isaza, A. Castellani, V. Gičev, B. Jeremić, E. Kalkan, V. Lee, S. Pezeshk, F. Rojas-Barrales, M. Stupazzini, M. Todorovska, M. Trifunac (Chair), and Z. Zembaty.

3.1 Key Issues and Unsolved Problems

One of the basic questions discussed was how large are the ground rotations exciting structures. When the structure is close to the fault surface, elementary linear theory indicates that the initial ground velocity is $\sim \sigma\beta/\mu$, where σ is the stress drop, β is the velocity of shear waves and μ is the rigidity of rocks surrounding the fault. Then the ground rotation is $\sim \sigma\beta/(\mu c)$, where c is the phase velocity. Dimensional analysis of these variables suggests large rotations, in the range from 10^{-3} to 10^{-2} rad, for earthquakes between magnitudes of 4 and 8. Such rotations were never recorded, so far. Furthermore those are only ”linear” amplitudes leaving the fault zone, which will be further modified by inhomogeneous materials along the wave path, surface topography and ultimately the nonlinear response of the soft materials near ground surface, which can easily account for additional one and perhaps two orders of magnitude (Trifunac 2008).

Beyond the results of linear theory, in the near field, surface soil experiences large nonlinear response and ultimately soil failure and liquefaction can lead to large transient and permanent motions. Lateral spreads will involve displacements of surface blocks of sediment facilitated by liquefaction in a subsurface layer. This type of failure may be particularly destructive to pipelines, bridge piers and other long and shallow structures situated in flood plain areas adjacent to rivers. Ground oscillations occur when the slopes are too small to result in lateral spreads, following liquefaction at depth. The overlying surface blocks break one from another and then oscillate on liquefied substrate. Flow failures are a more catastrophic form of material transport and usually occur on slopes greater than 3°. The flow consists of liquefied soil and blocks of intact material riding on and with liquefied substrate, on land or under the sea. Loss of bearing strength can occur when the soil liquefies under a structure. The buildings can settle, tip, or float upward, if the structure is buoyant. The accompanying motions can lead to large transient and permanent displacements and rotations, which were so far neither evaluated through simulation nor recorded by strong motion instruments. Consequently, any structure and in particular all extended structures (e.g. long buildings, bridges, tunnels, dams) in the area where such large nonlinearities in the soil occur, will, in addition to the horizontal components of inertial forces caused by strong earthquake shaking, experience large differential motions and large differential rotations of their foundation(s). Bridge peers, or foundations of long buildings, supported by soil, which the earthquake has separated into blocks by strong shaking, will be forced to deform in a manner accompanied by large differential motions (translations and rotations) of soil blocks, and will experience both inertial and pseudo static aspects of those motions. At present we can only speculate how much larger these motions will be relative to the tilts and angular accelerations and velocities we can estimate from the linear wave theory. Few observations however suggest that those can be orders of magnitude larger than the predictions based on the linear theory. For successful design, it will be necessary to prescribe the resulting forcing functions, which will include in a balanced way the simultaneous action of all components of possible motion. The description of how to scale those balanced forcing functions, can start from principles similar to what we use today for the design of structures crossing an active fault (Todorovska et al. 2007). Because the complexity of such motions and the multiplicity of possible outcomes will increase with amplitudes of incident strong motion waves, specification of the driving forces for design may best be formulated in terms of their distribution functions. This will require systematic and long-range research programs focusing on two key tasks: (1) Development of advanced numerical simulation models and (2) recording of all six components of strong motion, in the near field, and their analysis and interpretation. Such description of the near field motion will have to be used in the selection of design forces within distances, which are equal to about one source dimension (e.g. up to 20 to 50 km in California) away from the fault.

The power (energy and its duration) of the strong pulses in the near-field ground motion will determine whether the wave entering the structure will continue to propagate through the structure as a linear wave or begin to create nonlinear zones. For high-frequency pulses, the nonlinear zone, with permanent strains, can be created before the wave motion reaches the top of the structure—i.e., before the interference of waves (which leads to the formation of mode shapes) has even started to occur. As large waves propagate through the structure and deform its members beyond their linear range of response, the creation of nonlinear response zones and their localization (plastic hinges) will give rise to the zones of large local rotations (strains). These large rotations will also behave as waves, which will redistribute the available potential and hysteretic energies remaining after the passage of powerful pulses up and down the building. Recording these rotations can provide an invaluable tool for local damage detection. By placing small-aperture arrays of rotational transducers on beams and columns, it will be possible to achieve the next level in the resolution of point deformations because from closely spaced rotational sensors it will be possible to also record the point curvature.

The members of the panel were aware that it is not possible to compute accurately and reliably permanent displacements of the ground (or of structures) without simultaneously recording rotations during strong motion. This is not new. It was discussed by Graizer, 20 years ago in a series of articles (Graizer 1989a,b, 1991) and in the monograph entitled “True ground displacements in epicentral zone” (Graizer 1984). Unfortunately this important work appears to be ignored by most of the recently published papers. Recording rotations is essential for complete specification of the response of the horizontal acceleration transducers, and cannot be neglected for digital recorders with resolution grater than about 12 bits. Only the linearized form of the differential equation of the transducer recording vertical acceleration is not affected by strong motion tilting. All transducers however (vertical and horizontal) are affected by the angular accelerations, but the effect is relatively small, either because transducer arm is small, or because it is zero (depending on the details of the transducer design). The cross-axis sensitivity terms and misalignment terms have been analyzed in some detail (Todorovska 1998, Todorovska et al. 1998, Wong and Trifunac 1977). The cross-axis sensitivity errors are such that they add sharp pulses to the record of translational acceleration. In time these pulses coincide with the largest peaks of strong motion acceleration. After integrating twice, these peaks contribute to large “permanent displacements”, which, after all motion has stopped, will “grow” parabolically with time.

In the absence of recorded rotational components of strong motion, the spectral amplitudes of rotation are estimated from average Fourier spectra of translations and from synthetically computed accelerograms, based on linear wave propagation theory in layered soil and sediments. It is expected that such estimates are approximately correct in the far-field. In the near-filed, where the soil may experience nonlinear response, and the structures can be damaged, the rotational components of strong motion are expected to be larger than the linear estimates, and the need to include them in the analysis of motion is even more apparent.

The development and field deployment of instruments capable of recording all six components of strong motion, with resolution exceeding about 20 bits, will contribute to the next quantum jump in recording, interpretation and understanding of the near-field strong motion phenomena, and of permanent nonlinear and damaging response of structures. Until this is realized, the “standard” data processing methods will continue to work with band-limited acceleration, velocity and displacement. As the recording and digitization noise becomes smaller, this band will eventually broaden towards zero frequencies, and the computed velocities and displacements will converge to their true values that include permanent displacement. In the meantime, the available resources for recording strong motion should be optimized, avoiding excessive expenditures on high resolution and high dynamic range recorders where such high performance in recording translations only is not justified. Finally, it is hoped that the researchers who claim that “it is possible to recover the long period information from near-field strong motion accelerographs by an appropriate processing scheme,… using the proposed algorithm” will recognize that permanent ground displacement cannot be computed without the knowledge of the rotational components of strong motion, especially in the near-field of moderate and strong earthquakes where the response of the ground and structures may be nonlinear.

Recording angular components of strong motion will open innumerable new possibilities in engineering and seismological studies, especially in the near-field and in studies of nonlinear soil and structural response. Measured rotations will help identify and separate P and SV waves from SH components and Love from Rayleigh waves. Recording rotations near and on foundations of structures will help separate (from the total motions), and better identify the motions associated with soil-structure-interaction. Recorded rotational data will provide for the first time detailed picture of the relative interstory drift, by enabling us to separate the contributions of rocking from those of relative translational deformation. This will in turn help determine more realistic estimates of P-delta effects in full-scale structures. Simultaneous recording of all six components of motion will enable computations of permanent displacement in structures, soils and in the near field of ground near shallow earthquake faults. This enumeration could go on, but the benefits of recording all six components of motion are overwhelming, and should be obvious.

Panel members also discussed the vibrational (mode superposition) versus wave propagation formulation of the response of structures. It was recognized that the vibrational formulation is inadequate for representing the structural response to near-field strong motion pulses and that the wave propagation models of structural response to near-field strong motion pulses should be promoted and further developed. Mechanisms should also be devised for more systematic introduction and use of wave propagation methods in engineering education and in the practical structural analysis.

3.2 Research Strategy and Plans

Panel recommended the development and support of research programs to:

(1) Better understand and quantify rotational ground motions and their significance for structural design.

(2) Organize programs for recording rotational motions in structures to support advanced studies, such as structural health monitoring (e.g., detecting strain localizations due to damage), wave propagation methods for analysis of the seismic response of structures, calibration and validation of detailed finite element models of structures, foundations and soil-foundation-structure systems, and performance based design.

(3) Derive simplified formulae to include the effects of rotation in the building design codes.

(4) Conduct studies using analytical and numerical models for elastic an inelastic response of soils and soil-structure systems.

(5) Measure ground rotations and rotations in structures.

3.3 Specific tasks

The panel recommends that the following specific tasks be implemented to gather required data and to advance the engineering design process:

(1) Set up special purpose arrays in selected buildings, including rotational sensors and high resolution GPS, to provide data for advanced studies of structural response, such as structural identification and health monitoring, wave propagation methods for analysis of structural response, and performance based design.

(2) Upgrade the recording systems in many buildings to measure their rotational response during strong shaking,

with the objective to observe and identify the interaction of the structure with the foundation soil, and establish the role of soil-structure interaction in the response of full-scale structures.

(3) Set up detailed networks of rotational transducers in the free field, preferably collocated with existing arrays that have previously recorded useful data on strong motion translations. Use the recorded data to verify numerical simulation models, and calibrate relationships for estimating rotations from recorded translations, and future empirical scaling models for the amplitudes of the ground rotations.

(4) Establish permanent structural sites (buildings, bridges, dams, …) in seismically active regions of the world to serve as full-scale laboratories for studies of the response of structures in the nonlinear range of response.

(5) Develop guidelines for structural array configuration and practical installation of rotational sensors in structures. This task can be facilitated by conducting full-scale tests.

(6) Investigate the effect of the rotation of the instrument box on the recorded translations (of the ground and in structures), and on displacements computed by double integration of the recorded accelerations. Investigate the implications of the errors in calibration of structural models from using liner vibrational records in structures.

(7) Investigate how information from rotational sensors can be used for validation of detailed numerical models of structures, foundations and soil-foundation-structure systems.

(8) Carry out detailed numerical simulations of the nonlinear response of soil-structure systems to understand the basic properties of their rotational motions. Compare these simulations to results based on different modeling techniques (significant variations may exist depending on the choice of input model parameters and modeling technique).

(9) Carry out detailed numerical simulations of the effects of topography and inhomogeneity of soils and rocks beneath structures on the ground rotations exciting structures, and identify conditions that enhance the amplitudes of the ground rotations.

(10) Further analyze data from existing dense arrays of translational sensors to estimate ground rotations using spatial derivatives.

(11) Develop modeling techniques for simulation of the rotational components of strong ground motion.

(12) Set up a Web site(s) for free dissemination of translational and rotational strong motion data.

(13) Promote various aspects of research and education dealing with rotational strong motion.

3.4 Summary, Recommendations and Conclusions

The average rotation between floors in a structure (drift) is at present the key variable that governs the engineering design of structures to withstand destructive motions caused by earthquakes, strong winds, and explosions. During strong earthquakes, this rotation results from: (i) the rotational components of seismic waves, (ii) the interaction of the structure with the flexible soil, and (iii) the relative deformation of the structure by the inertial loads. Accurate prediction of all of those contributions to the average rotations (drift) is essential for the engineering design to be conservative.

The lack of recorded data on the rotational components of strong motion, and the complexity of the treatment of the interaction between vibrating structures and the supporting flexible soil have resulted in simplified engineering design which considers only the translational components of the strong ground motion and of the structural response. This approximation may be adequate only at large distances from the earthquake fault but leads to serious underestimation of the response amplitudes in the near field and adjacent to the fault.

To properly include the effects of the rotational components of strong ground motion in realistic design criteria of structures, it is essential that: (1) the rotational components of motion are recorded both in the soil and in the structures, and (2) engineering education be modernized to include studies of wave propagation, so that eventually the realistic performance design methods can be developed, and the building code design formulae will include the effects of the rocking and torsional motions resulting from soil structure interaction.

These objectives can be accomplished during the next several decades by initiating and maintaining comprehensive observational and educational programs. In addition to the work for building codes, which are concerned with minimum design to insure life safety, recording rotations in structures is also necessary for advanced uses of vibrational records in structures, such as those that required for detailed description of the structural response, for accurate estimation of the structural parameters and its performance. Such uses include structural health monitoring and early warning of earthquake damage in structures, development of advanced performance based design, and system identification for calibration of realistic soil-structure models.

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