Department of Geophysics
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2nd International workshop on Rotational Seismology and Engineering Applications

Programme & Abstracts

Masaryk's College, Prague — October 10–13, 2010

Acknowledgements:

The workshop is co-sponsored by the Department of Earth and Environmental Sciences, LMU Munich, the Charles University in Prague and the EU-funded QUEST project.

Meeting Programme

Sunday, October 10th

17:30	Registration of participants
19:00	Icebreaker

Monday, October 11th

8:00 – 9:00	Registration of participants
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9:10 – 9:40	Why Rotation Seismology: Confrontation between Classic and Asymmetric Theories, *R. Teisseyre* (p. 8)
Instrumentation (chair: J. Wassermann)	
9:40 – 10:00	Progress in Ring Laser Technology, *K.U. Schreiber, A. Gebauer, and Th. Klügel* (p. 8)
10:00 – 10:20	Installation of the ringlaser G-Pisa inside the Virgo area, *A. Di Virgilio, J. Belfi, N. Beverini, F. Bosi, G. Carelli, E. Maccioni, R. Passaquieti, and F. Stefani* (p. 9)
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10:40 – 11:00	Environmental Effects in Rotation Data from the Large Laser-Gyroscope 'G', *A. Gebauer, U. Schreiber, and T. Klügel* (p. 11)

11:00 – 11:30 *Coffee break*

Instrumentation (chair: H. Igel)

11:30 – 11:50 Pilot sensors for rotation strong motion recording, *Kozák, J., J. Buben, P. Jedlička, and J. Knejzlík* (p. 11)

11:50 – 12:10 Rotaphone – A Self-Calibrated Mechanical Seismic Sensor for Field Rotation Rate Measurements, *J. Brokešová and J. Málek* (p. 12)

12:10 – 12:30 Performance of new R-2 Sensor, *J. R. Evans, C. R. Hutt, R. N. Nigbor, and T. de la Torre* (p. 13)

12:30 – 12:50 Fiber Optic Gyroscope as a tool for detection of seismic rotations, *A. Velikoseltsev, K. U. Schreiber, A. Yankovsky, A. Boronachin, and A. Tkachenko* (p. 14)

13:00 – 14:30 *Lunch*

Instrumentation (chair: J. Brokešová)

14:30 – 14:50 AFORS – Autonomous Fibre-Optic Rotational Seismograph Design and Application, *L. R. Jaroszewicz and Z. Krajewski* (p. 15)

14:50 – 15:10 Rotational Seismometer on the Capacitive Principle, *J. Štrunc* (p. 16)

15:10 – 15:30 Generator of Seismic Rotational Motions, *J. Málek and J. Brokešová* (p. 16)

15:30 – 15:50 Rotation Sensor Requirements for Exploration Seismology, *E. Muyzert* (p. 17)

15:50 – 16:10 *Coffee break*

16:10–17:30 **Poster session**

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New Portable Mechanical Sensor System for Rotational Seismic Motion Measurements, *J. Brokešová and J. Málek* (p. 18)

Adaptation of pendulous seismometer S-5-S for measurement of rotation component of seismic vibrations, *J. Knejzlík, Z. Kaláb, and Z. Rambouský* (p. 19)

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9:40 – 10:00	On a Possibility of Acquiring Strong Motion Rotation from Rockburst Effects, *Zbigniew Zembaty* (p. 27)
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10:40 – 11:10	*Coffee break*

Strong Rotational Motions (chair: J. Málek)

11:10 – 11:30	Tilt Errors on Recorded Accelerations from Instrumented Structures, *E. Kalkan and V. Graizer*
11:30 – 11:50	The Effect of Rocking Component of Strong Ground Motion on the Structural Response, *G. R. Nouri* (p. 32)

12:00 – 13:30	*Lunch*

Theory and Applications (chair: V. Graizer)

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14:20 – 14:40	Observations of Long-Period Rotational Ground Motions: From ambient noise to Earth's Free Oscillations, *H. Igel, D. Kurrle, A. Ferreira, J. Wassermann, P. Gaebler, and U. Schreiber* (p. 36)
14:40 – 15:00	Inverting Ground Motion from a Seismometer Array to obtain the Vertical Component of Rotation: A Test Using Data from Explosions, *W. Chi, W. Lee, C. Lin, J. Aston, and C. C. Liu* (p. 37)
15:00 – 15:20	Back Calculation of Earthquake-Rotated Objects (EROs), *K. Hinzen* (p. 38)
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15:40 – 17:00	General discussion
19:00 – 19:45	Concert
20:00	Conference dinner

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Applications (chair: A. Castellani)

9:00–9:20	Research on Rotational Components of Ground Motion in Wenchuan Earthquake, *Q. Luo, Z. Hong, and C. He* (p. 39)
9:20–9:40	Torsional motion Due to Small-Scale Geological Irregularity, *M. R. Ghayamghamian* (p. 39)
9:40–10:00	Using the Wavelet Transform to Estimate Instantaneous Tilts, *A. Chanerley, and N. Alexander* (p. 40)
10:00–10:30	*Coffee break*
10:30–12:00	General discussion and Closing of the workshop
12:00–13:30	*Lunch*

Abstracts

Why Rotation Seismology: Confrontation between Classic and Asymmetric Theories

Roman Teisseyre
Institute of Geophysics, Polish Academy of Sciences, Poland

Monday, October 11th, **9:10–9:40**

A confrontation between the Classic Elasticity and Asymmetric Continuum Theory is presented in order to indicate the abilities of the two approaches and their deficiencies. The role of independent strain and rotation waves is discussed and some related particular examples are given. Our consideration may answer the question why the new theoretical approach might be important in a search for new earthquake precursory signals.

Progress in Ring Laser Technology

U. Schreiber, A. Gebauer, and Th. Klügel
Technische Universitaet München, Germany

Monday, October 11th, **9:40–10:00**

Over the last year we have improved the technology by as much as a factor of 3, which makes the domain of $\Delta\Omega/\Omega \approx 10^{-9}$ of Earth

rotation accessible to a local rotation sensor. As a result of these efforts eigenmodes of the Earth, excited by strong earthquakes have become observable.

Recent efforts concentrate on the extension of the sensor stability against a drift induced by atmospheric pressure variations and the corresponding temperature changes from adiabatic expansion and compression of the local air as well as a new approach in local sensor orientation effects. This talk outlines recent progress in Sagnac interferometry.

Installation of the ringlaser G-Pisa inside the Virgo area

Angela Di Virgilio[1], *J. Belfi*[2], *N. Beverini*[2], *F. Bosi*[1], *G. Carelli*[2], *E. Maccioni*[2], *R. Passaquieti*[1,2], *and F. Stefani*[2]

[1] INFN-Pisa, Italy

[2] Univ. of Pisa and CNISM, Italy

Monday, October 11th, **10:00–10:20**

G-Pisa is a middle size ringlaser (1.35 m side). In June 2010 it has been installed inside the central area of Virgo, the 3 km interferometer for the research of gravitational waves. Ringlasers, as inertial sensors of rotation, are potentially very interesting devices for the so called third antenna generation. The main purpose of our present experiment is to measure the environmental disturbances, especially in the frequency range 1-0.001 Hz and for the tilts motions, which are responsible of degradation of the antenna performances during severe weather conditions. Our prototype has the sensitivity required by Virgo: from 10 mHz. The installation is described in details and the preliminary analysis reported.

G-Pisa gyrolaser: Operational details and Remote control systems

N. Beverini[1,2], *J. Belfi*[1,2], *G. Carelli*[1,2], *A. Di Virgilio*[2], *D. Kolker*[3], *F. Stefani*[1,2]

[1] Dipartimento di Fisica dell'Università di Pisa (Italy)

[2] INFN, Sezione di Pisa (Italy)

[3] Technical State University of Novosibirsk (Russia)

Monday, October 11th, **10:20–10:40**

As presented in a different communication1, a square shaped laser gyroscope, 1.35 m in side, has been installed in the central hall of the Virgo experiment. The apparatus was intended to work in unattended way during the Virgo acquisition runs. For this purpose, we had to implement a robust active stabilization system that could be controlled by remote, and an automated acquisition system of the rotational signal and of the diagnostic data.

Besides the Sagnac interference signal, produced by the radiation transmitted from one of the ring mirrors, we sample also by two photodiodes the intensity signals of the two counterpropagating beams transmitted from a second ring mirror. This signal is used to stabilize in the long term the value laser emission intensity by acting on the He-Ne discharge excitation power. Finally, the clockwise radiation transmitted from a third mirror is collected in an optical fiber and sent in a scanning Fabry-Pérot interferometer in order to measure its wavelength by compared with a reference He-Ne laser. A servo circuit stabilizes this wavelength by acting in parallel on two mirrors in opposite position through two PZT's.

All the operations of the servo circuits and of the data acquisition are governed by two PC's that can be controlled from remote position through Internet connection.

Environmental Effects in Rotation Data from the Large Laser-Gyroscope "G"

A. Gebauer, U. Schreiber, T. Klügel
Technische Universitaet München, Germany

Monday, October 11th, **10:40–11:00**

Large laser gyroscopes allow the observation of the global rotation rate of the Earth and provide a direct reference to the instantaneous axis of rotation with high temporal resolution. This measurement method is independent and complementary to the VLBI technique, because it does not depend on external reference objects. Long periodic signals from geophysical processes are analyzed in the measured datasets Thus more geophysical processes both on global and local scale become visible. The time series of the measurements also contain irregular transient signals of different origin and magnitude. Several studies were carried out to identify the origin of these signals. First studies showed that the contribution of barometric loading is too small to account for the observed rotational signals. Then the effect of wind load on a local scale was studied. A detailed Finite-Element (FE) Model was developed with a dimension of about 10 km x 10 km and a minimum height of about 2 km. The topography is derived from a digital terrain model (DTM) of 25 m spatial resolution. Depending on the topography and land use the measured wind force loads the model. The results yields rotations in comparable order of magnitude as the observed ring laser data in the period ranging from about 30 seconds to several minutes.

Pilot sensors for rotation strong motion recording

J. Kozák[1], *J. Buben*[2], *P. Jedlička*[1], *and J. Knejzlík*[3]
[1] Institute of Geophysics, Acad. Sci., Czech Republic
[2] Institute of Geology, Acad. Sci., Czech Republic
[3] Institute of Geonics, Acad. Sci., Czech Republic

Monday, October 11th, **11:30–11:50**

Within the running Czech-USA AMVIS Grant on "Fluidal Seismo" sensor, several variants of rotation seismographs were designed, built and preliminarily tested:
a)Pendulum with rotation axis made of flat crest springs. For displacement-voltage conversion an electro-magnetic convertor was used,
b)Solid-state disc bob fixed on a spindle imbeded in bearings, equiped with capacity or electromagnetic transducer,
c)Fluidal inertial mass in a ring-shaped tube equiped with i)electromagnetic, ii)tensometric, iii)pressure-voltage transducer.
Preliminary results obtained during field and laboratory testing of the above sensors are presented and discussed.

Rotaphone – A Self-Calibrated Mechanical Seismic Sensor for Field Rotation Rate Measurements

J. Brokešová[1], *J. Málek*[2]
[1] Charles University in Prague, Czech Republic
[2] Institute of Rock Structure and Mechanics, Acad. Sci., Czech Republic

Monday, October 11th, **11:50–12:10**

Rotaphone is a newly developed mechanical sensor system for recording the rotation rate components. It is based on measurements of differential motions between paired sensors (low-frequency geophones) attached to a rigid undeformable) skeleton. The same differential velocity (and, consequently, the same rotation rate component) is obtained from more than one geophone pairs, which allows for in-situ calibration of individual sensors. The calibration method is explained in detail. It is demonstrated on two illustrative examples: a synthetic test and a laboratory test.

The Rotaphone is characterized by a flat frequency characteristic in the wide range from 2 Hz to 100 Hz and sensitivity limit of the order of 10^{-8} rad/s. Its advantages are small dimensions, portability, easy installation and operation in the field. We present several examples of the vertical rotation rate ground motion recorded by this device in Western Bohemia earthquake swarm area. Sources of the recorded rotation rates are both natural (microearthquakes) and antropogenic (blasts). Under the assumption of a plane wave propagating along the surface, selected records are compared to the corresponding transverse accelerograms. The limits of such approach in the area of interest are discussed.

Performance of new R-2 Sensor

J. R. Evans[1], *C. R. Hutt*[1], *R. N. Nigbor*[2], *and T. de la Torre*[3]
[1] U.S. Geological Survey, USA
[2] Department of Civil Engineering, UCLA, USA
[3] Department of Geological Sciences and Cooperative Institute for Research in the Environmental Sciences University of Colorado at Boulder, USA

Monday, October 11th, **12:10–12:30**

The Eentec R2 is designed for strong-motion seismic and engineering applications and has sensitivity of roughly 50 V/(rad/s), hard-clip level of about 0.1 rad/s, and a "flat" response band is cited as 0.03 to 50 Hz. It has lower noise at low frequencies and comparable or higher noise at high frequencies, compared to the R1; it is hoped to be less prone to internal corrosion than the R1 because the R2 sensing torus is plastic.

At the Albuquerque Seismological Laboratory (ASL) we tested 12 new R2s to characterize their noise performance and amplitude response functions. We also looked at translation-to-rotation cross axis sensitivity in two examples (this cross-axis term must be very low in typical seismic and engineering applications to be useful in correcting for rotation-induced gravitational inputs to horizontal accelerometers. Finally, inspection of the sensors as received from the manufacturer revealed generally good construction. However, contaminants were present in all 12 devices, commonly including aluminum shavings that can cause electrical shorts (we removed this debris). There was also a white to beige crystalline deposit around most of the plug screws sealing the fluid-filled sensing tori. Two other construction anomalies were also found, a sensing torus with a large bubble and one Z axis oriented upside down to the others (Table 1).

At low frequencies R2 instrument noise is well below the R1 and at higher frequencies comparable or higher. Overall rms noise levels are on the order of 1–5 μrad/s rms, with a number of exceptions. Spike-like noise is present on many channels; a minority of these spikes are large enough and of long enough duration to make an earthquake record useless but most are of very brief duration and are fairly uncommon in any two-minute record (i.e., typical earthquake duration). Baseline stability (in terms of errors in rotation-corrected horizontal translational displacement) appears adequate for records of several minutes duration. Amplitude response functions, if first normalized to unity at 4 and if compared over only 0.1 to 20 Hz, are mostly within $\pm$3 dB flatness; some deviate more at frequency extremes within the full pass band of 0.03 to 50 Hz. Even these normalized response functions are not as flat as for most sensors, including that no channels are within $\pm$1 dB of flat ($\sim$12% amplitude variation).

Fiber Optic Gyroscope as a tool for detection of seismic rotations

A. Velikoseltsev[1], *K. U. Schreiber*[2], *A. Yankovsky*[3], *A. Boronachin*[1], *A. Tkachenko*[1]

[1] St.-Petersburg Electrotechnical University, Russia

[2] Technische Universitaet Muenchen, Germany

[3] Nova Southeastern University Oceanographic Center, USA

Monday, October 11th, **12:30–12:50**

In the recent years the measurement of rotational components of earthquake induced ground motion became a reality thanks to the extremely high resolution instrumentation, namely the arge ring laser gyroscopes. Based on Sagnac effect, these devices are fully insensitive to translational motion and are able to measure the rotation rate with high linearity and accuracy in the wide frequency band. During the last decade substantial number of earthquakes was recorded by the large ring lasers located in Germany, New Zealand and USA, and the subsequent data analysis demonstrated reliability and consistency of the results with theoretical models. However most of the observations are done for teleseismic events and the substantial mass-dimensional characteristics of these devices make their near-field application difficult. Therefore another type of optical rotation sensors, which utilizes the same Sagnac effect as a principle of operation, may be used for seismic applications where mobility factor is more important than extreme precision. These sensors called fiber optic gyroscopes and their reasonable accuracy combined with small size make them perfect candidates for such missions. In this paper we analyze a typical commercially available fiber optic gyroscope with respect to the seismic rotation measurement requirements and present its initial test results.

AFORS – Autonomous Fibre-Optic Rotational Seismograph Design and Application

L. R. Jaroszewicz, *Z. Krajewski*
Institute of Applied Physics/Military University of Technology, Poland

Monday, October 11th, **14:30–14:50**

In this presentation we conclude research and development according the Autonomous Fibre-Optic Rotational Seismograph - AFORS. The presented device with linear changes of the sensitivity protects accuracy from $5.1 \cdot 10^{-9}$ to $3.9 \cdot 10^{-8}$ rad/s in detection bandpass 1.66–106.15 Hz, is designed for direct measurement the rotational components exist in seismic events. The presented system bases in optical part on the fibre optic gyro construction where the special autonomous signal processing unit – ASPU optimizes its operation for measurement rotation speed instead angular changes. The application a new design telemetric system bases on internet allows for remote system control as is shown in example of system work in Ksiaz (Poland) seismological laboratory.

Rotational seismometer on the capacitive principle

Jaroslav Štrunc

Institute of Rock Structure and Mechanics, Acad. Sci., Czech Republic

Monday, October 11th, **14:50–15:10**

A novel approach based on the direct measuring of rotations using sophisticated mechanical transmission of ground movement into change of capacitance between electrodes of capacitor will be presented. It enables to construct small and portable sensor for field measurement. The other current methods for studying seismic rotations depend on the indirect measurement by means of matrix of sensors requiring careful in-situ planning. Basic ideas, dynamic characteristics, realized sensor, data acquisition module, algorithms and their implementations are discussed on a prototype of sensor. Sensor fulfils all requirements for general seismic measurement and complies with seismological standards so that it can be operated within any existing seismic network.

Generator of seismic rotational motions

J. Málek[1], *J. Brokešová*[2]

[1] Institute of Rock Structure and Mechanics, Acad. Sci., Czech Republic

[2] Charles University in Prague, Czech Republic

Monday, October 11th, **15:10–15:30**

Two prototypes of mechanical generator of seismic rotational motions are presented. Generator is anchored with its fixed part in the ground, and the mobile (rotary) part of the generator, after being activated, is stopped instantaneously by the braking mechanism; this instantaneous stopping transmits energy into the rock massif. An advantage of the generator is its relatively small dimensions and weight, which makes it easy to move in the field. The generator is designed to be used for sequentially repeated experiments, so that essentially the same pulse of rotational seismic waves is generated. The signals from repeated measurements may also be combined in the control unit in order to achieve high sensitivity by suppressing noise via stacking. Non-linear combination of signals can be applied for this purpose. The generator is intended for use in a measuring set together with mechanical rotational sensor system (Rotaphone).

Rotation sensor requirements for exploration seismology

E. Muyzert
Schlumberger Cambridge Research, UK

Monday, October 11th, **15:30–15:50**

Rotational seismology may contribute to solving some of the longstanding challenges in exploration seismic including near surface perturbations, noise (ground-roll) attenuation, velocity estimation and imaging. It is most likely that for any proposed solution the rotation data will be combined with geophone data. For most applications this would require that the rotation data is measured with similar accuracy as the geophone data. We analyse the geophone specifications and derive rotation sensors requirements from it. These include expected frequency response, dynamic range and practical considerations. An ambient noise model is also derived which shows that current sensors need considerable lower self noise levels. The aim of this analysis is set targets for development of exploration rotation sensors that can hopefully be met in the future.

Rotational Sensor R1 – A Performance Test

F. Bernauer, J. Wassermann, and H. Igel
LMU Munich, Germany

Monday, October 11th, **16:10–17:30**

Object of our test was the rotational seismometer R1 manufactured by Eentec. The basic operating principle of the R1 is that incoming ground movement is transduced into an electrical voltage output by an electrochemical sensor. This sensor contains an electrolytic fluid as transducing medium. As the properties of fluids (diffusivity, viscosity, etc.) vary strongly with temperature we where suspicous of the nominal operating temperature, that ranges from -15 up to 55 degrees of Celsius. For the test we used the steptable CT-EW01 with an attached bridge that gives a constant input rotational motion signal. Comparing this input signal to the output of the R1 at four different temperatures (20, 30, 40 and 50 degrees of Celsius) we found that the generator constant deviates up to 30% from the nominal value of 50 Vs/rad . Two more tests on stability of the generator constant with respect to time and high gain input and one simple noise test were carried out.

New Portable Mechanical Sensor System for Rotational Seismic Motion Measurements

J. Brokešová[1] *and J. Málek*[2]
[1] Charles University in Prague, Czech Republic
[2] Institute of Rock Structure and Mechanics, Acad. Sci., Czech Republic

Monday, October 11th, **16:10–17:30**

A new mechanical sensor system for recording the rotational components of ground velocity in a horizontal plane has been constructed. It was tested both in a laboratory and in a field experiment. The sensor system is based on measurements of differential motions between paired sensors mounted along the perimeter of a rigid (undeformable) disc. The elementary sensors creating the pairs are sensitive low-frequency geophones with equal frequency response. The main features of the new rotational seismic sensor system is a flat frequency characteristic in the wide range from 2 Hz to 100 Hz and sensitivity limit of the order of 10^{-8} rad/s. Notable advantages are small dimensions, portability, easy installation and operation in the field. An important feature of the instrument is that it provides records of translational seismic motions together with rotations, which allows many important seismological applications. We have used the new sensor system to record the rotation velocity in a horizontal plane due to a small earthquake of $M_L = 2.2$, which occurred within the earthquake swarm in Western Bohemia in autumn 2008. We found good agreement of the rotation record with the transverse acceleration, as predicted by theory. This measurement demonstrates that this device has a much wider application than just prospecting measurements, for which it was originally designed.

Adaptation of pendulous seismometer S-5-S for measurement of rotation component of seismic vibrations

Jaromír Knejzlík, Zdeněk Kaláb, and Zdeněk Rambouský
Institute of Geonics, Acad. Sci., Czech Republic

Monday, October 11th, **16:10–17:30**

Modification of seismometer S-5-S for measurement of rotation component of seismic vibrations is described. Mechanical system of S-5-S consists of sensing and dumping electrodynamical transducers mounted on unsymmetric two-arm pendulum which is suspended by two cross flat spring hangings. Pendulum is balanced by spring. Described modification of S-5-S consists of removing of the spring and balancing of pendulum by supplementation of additional mass on the damping arm. Additional strain-gauge sensor of rotation displacement is installed on flat springs hanging. Main dynamic parameters of resulting rotation sensor, e.g. natural period and damping of sensor, are controlled by feedback signals of rotation displacement and rotation velocity that are conducted to the damping transducer. Sensor enables measurement of movement around vertical or horizontal axes. Output signal can be proportional to the rotation displacement or rotation velocity.

Using Rotational Sensor Data to Correct Rotation-Induced Effects on Accelerometers

C. Lin[1], *C. Liu*[1], *J. Evans*[2], *W. Lee*[2], *H. Huang*[3]

[1] Institute of Earth Sciences, Academia Sinica, Taiwan

[2] U.S. Geological Survey, USA

[3] Dept. of Mechanical Engineering, National Taiwan University, Taiwan

Monday, October 11th, **16:10–17:30**

Dynamic and permanent seismic displacements are important for seismologists and engineers and, in principle, can be derived from the double time integral of translational acceleration. However, because translational accelerometers are sensitive not only to translational but also to rotational motions, it is not possible to recover with assurance the true displacement by direct double time-integration of acceleration without first applying corrections from separately recorded rotational motions.

We apply an attitude equation from the navigational literature to obtain the time-dependant orientation of the accelerometer from collocated recordings of three-axis rotation rate, then applies an attitude-correction equation together with orientation and these rotational data to correct centrifugal and tilt-induced gravitational ef-

fects on accelerometers. Finally, we perform coordinate transformations to derive the dynamic motion in an inertially fixed (geographic) coordinates frame rather than in the body-attached coordinates in which they are recorded.

To verify our algorithm, we attached a three-axis translational accelerometer and a three-axis rotation-rate sensor together to the end of a robot arm. By moving the robot arm simultaneously in translation and rotation, we find a good match between displacements calculated with our correction scheme and the actual robot arm movements, as determined by the robot's inputs and feedback system.

In-situ calibration of seismic sensors recording differential motion to determine rotational ground motion components

J. Málek[1], *J. Brokešová*[2] *and P. Kolínský*[1]

[1] Institute of Rock Structure and Mechanics, Acad. Sci., Czech Republic

[2] Charles University in Prague, Czech Republic

Monday, October 11th, **16:10–17:30**

We present an effective in situ calibration of paired sensor records used to determine differential seismic motions. The calibration is of extreme importance when small differential motions are to be recorded, which requires the paired sensors to be 'identical' in terms of their frequency characteristics. These differential motions are subsequently used to derive finite differences approximating spatial derivatives appearing in the expressions for seismic rotations. The calibration method is applicable only when the differential motions are over-determined, i.e. the same difference is measured by more than one pair of sensors of the same type. We demonstrate the calibration method on three illustrative examples: a synthetic test, a series of laboratory tests using a special rotational shaking table, and a measurement of vertical rotation rate due to a small earthquake of

$M_L = 2.7$, which occurred within the earthquake swarm in Western Bohemia in autumn 2008. We found good agreement of the calibrated rotation record with the transverse acceleration as predicted by theory.

The attempt to model rotations in the Coda with Radiative Transfer Theory

C. Sens-Schönfelder, *K. Neupert*
Universität Leipzig, Germany

Monday, October 11th, **16:10–17:30**

The wave field that makes up the high frequency coda of seismic signals is a complex superposition of waves with different direction. These waves cause ground rotations. The success of modeling the coda of traditional translational seismograms with Radiative Transfer Theory (RTT) led to the idea to model also the envelopes of rotational motions. As a new observable the rotational measurements may help to constrain information about the heterogeneity of the medium. We present the concept of RTT and show how it can be used to obtain information about the medium from seismogram envelopes. The strategy to model rotational motions is presented and we show first simulations for rotational motions in the coda of teleseismic P-waves.

New Rotational Seismometer

D. Smith, *D. Laughlin*, *A. Cline*
A-Tech Inc.,USA

Monday, October 11th, **16:10–17:30**

Applied Technology Associates produced a rotational seismometer in the early 1990s to solve a dynamic control problem of the Seismically Stable Platform on Holloman Air Force Base in New Mexico, USA. ATA is again answering the call for a rotational seismometer suitable for correcting linear seismometer measurement for g * sine theta disturbances caused by rotations. ATA will present preliminary performance predictions and an update on progress toward achieving a fieldable instrument. ATA has also recently developed an instrument to detect inertial north. The device is immune to magnetic disturbances and is tolerant of thermal variations. Performance and current configuration will be presented.

Spin and Twist Motions in the Earthquake Preparation Processes: Analysis of Records

Krzysztof Teisseyre
Institute of Geophysics, Polish Academy of Sciences, Poland

Monday, October 11th, **16:10–17:30**

Several seismic events were chosen for comparative analysis of two kinds of seismic motions: spin (rotation velocity) and twist (shearing oscillations). These components of the seismic field were detected in horizontal plane with a pair rotational seismometers (assembled in the Institute of Geophysics, PAS). Curve of one component was compared to the other directly and after transformations, as a phase-shifting. Homologous parts were found in this way in the signals of spin and twist components. Conformities of spin and twist are assumed to be effects of processes that occurred in the focus, both during the seismic event and in the preceding phase of direct preparation to the rupture.

Current Status of Rotational Seismology Studies in PKU-CEA Joint Research Center of Modern Seismology of China

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Monday, October 11th, **16:10–17:30**

To promote rotational seismology studies in China, we are planning to deploy rotational seismological network in seismic active regions in China. This short communication describes current status of the research plan and the ideas for future development direction.

Phase velocity and source direction estimation using collocated measurements

Peter Gaebler
LMU Munich, Germany

Monday, October 11th, **16:10–17:30**

We introduce a study, in which the possibility of determining surface wave phase velocities and source directions from collocated measurements of translational and vertical rotational motions excited by ambient seismic noise sources is investigated.

Assuming plane, horizontally polarized shear waves, the information about the local phase velocity is contained in the amplitude ratio of transversal acceleration and rotation rate.

The first set of data consists out of data recorded at the geodetic observatory in Wettzell using the high quality rotational motion ringlaser sensor and the collocated STS2-broadband seismometer. Data analysis shows the possibility of determining local phase velocities from ambient seismic noise data in the primary and secondary oceanic microseisms frequency band. Furthermore it is possible to estimate the backazimuthal direction of the generating areas of oceanic microseisms.

An additional data set was acquired using the portable angular motion sensor R1 and a Trillium compact broadband seismometer in field operation. Data analysis in the microseisms frequency band clearly showed the necessity of higher quality and more sensitive portable angular motion sensors. Investigations of ambient noise in the frequency band above 10 Hz were compared with results derived from seismic array measurements and show a clear consistency in the phase velocity estimation.

Strong motion seismology and rotations: history and future directions

V. Graizer[1], *E. Kalkan*[2]

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Tuesday, October 12th, **9:10–9:40**

Since the beginning of strong ground motion networks in the mid 1930s thousands of 3-component large amplitude recordings were collected. Most common strong motion instruments are pendulums of the mass-on-rod type designed to record translational acceleration. Original method of data processing allows for calculation of translational acceleration, velocity and displacement within a limited frequency range (Trifunac, 1969). Since 1980s new generation of digital instruments has been replacing film recorders. With higher resolution instruments and a number of accelerograms recorded in the vicinity of faults, scientists also attempted to recover residual displacements (Graizer 1979; Iwan et al. 1985). Limitation of strong motion data processing is due to the resolution (dynamic range) of the instruments, and its sensitivity to tilts (Graizer 2005, 2010).

Starting from 1970s researchers in different countries were attempting to measure or estimate rotations during strong earthquake motions. But only recently this area started getting attention with new instruments designed to record rotations, and the realization of scientific and engineering importance of rotational component of ground motion. Besides laboratory and field testing of new instruments there is a need to provide mathematical description of their response in a way similar to that of a pendulum response.

In mean time large collection of existing strong motion recordings allows at least in some cases for extracting tilts from the records. The method of tilt evaluation using uncorrected strong-motion accelerograms was developed and tested numerically and experimentally (Graizer, 1989, 2006). The method is based on the difference in the tilt sensitivity of the horizontal and vertical pendulums and requires usage of uncorrected records. It was applied to a number of strongest free-field and building records of the 1994 M_W 6.7 Northridge earthquake. Relatively large tilts of up to a few degrees occurred during strong ground shaking. Residual tilt extracted from the strong-motion record at the Pacoima Dam – Upper Left Abutment reached 3.1 degrees in NE direction, and was a result of local earthquake induced tilting due to high amplitude shaking. Processing of most of the strongest free-field and building records of the Northridge earthquake shows that tilts, if happened, were within the error of the method, or less than about 0.5 degree. In a few cases including buildings damaged during Northridge earthquake tilts in buildings reached few degrees during the strongest shaking. For example, residual tilt of about 1 degree was recovered at the Los Angeles code instrumented building Woodland Hills – Oxnard #4. According to a number of studies this 13-story office building sustained significant damage during the Northridge earthquake. Residual tilts from 0.4 up to 3.5 degrees were also calculated for the four locations at the Los Angeles – 6-story building (CSMIP station 24652) during the Northridge earthquake. Residual tilts extracted from the records can be interpreted as another sign of building damage.

Dynamic response of most seismological instruments and many engineering structures to ground shaking can be represented via response of a pendulum. We considered complete equations of motion for different types of pendulum: (i) conventional (mass-on-rod), (ii) mass-on-spring type, and (iii) inverted (astatic). The response sensitivities to each component of complex ground motion are examined using close-form solutions in time-domain given by the Duhamel's integral (Graizer and Kalkan, 2008). The results of this study show that a horizontal pendulum similar to an accelerometer used in strong motion measurements is practically sensitive to translational motion and tilt only, while inverted pendulum commonly utilized to idealize multi-degree-of-freedom systems is sensitive not only to translational components, but also to angular accelerations and tilt. For better understanding of the inverted pendulum's dynamic behavior under complex ground excitation, relative contribution of each component of motion on response variants is carefully isolated. The systematically applied loading protocols indicate that vertical component of motion may create time-dependent variations on pendulum's oscillation period; yet most dramatic impact on response is produced by the tilting (rocking) component Kalkan and Graizer, 2007a,b).

On a possibility of acquiring strong motion rotation from rockburst effects

Zbigniew Zembaty
Opole University of Technology, Poland

Tuesday, October 12th, **9:40–10:00**

Usually rockbursts from underground deep mining produce surface peak ground accelerations (PGA) of 0.05–0.1 g and velocities (PGV) 1–3 cm/s, leading to maximum MM intensities of these events of about III–V. Depending on the mine basin such events happen with approximate return period of about 1–3 months. Occasionally, every 1–2 years the magnitude of these rockbursts reach $M_L = 4.5$ to 5.0 and the peak motions may reach PGA=0.2 g and PGV=20 cm/s or more, with strong motion duration of about 5 s [1, 2]. Such strong ground motions are of concern of the mine authorities, particularly when the deep mining takes place in the urban areas.

When compared with other artificial or semi-artificial seismic effects like traffic vibrations, underground blasts or reservoir induced seismicity the rockburst effects can be placed close to nuclear underground explosions with respect to their surface intensity, but with mechanisms more similar to natural earthquakes measured in very close near field and shallow focal depths 1–2 km [3]. Thus there is a convenient opportunity to quite effectively acquire strong rotational ground motion in a span of 3–4 years in an active basin of deep mining.

The purpose of the presentation planned for the Workshop is to present in detail the rockburst seismic effects as a possible source of rotational strong ground motion.

References

[1] Zembaty Z., Rockburst induced ground motion—a comparative study, Soil Dynamics & Earthquake Engineering, vol. 24, 2004, pp.11–23

[2] Zembaty Z., Non-stationary random vibrations of a shear beam under high frequency seismic effects, Soil Dynamics & Earthquake Engineering, vol. 27, 2007, pp. 1000–1011

[3] Gibowicz S.J., Kijko A., An introduction to mining seismology, Academic Press, San Diego 1994

Rotational Component Effects in Modern Seismic Codes

M. R. Falamarz-Sheikhabadi, *M. Ghafory-Ashtiany*

International Institute of Earthquake Engineering and Seismology, IIEES, Iran

Tuesday, October 12th, **10:00–10:20**

The paper addresses the issue of investigation of the characteristics of the rotational components and the need of regarding their influences on seismic loading of resistant structures against Strong

Ground Motion (SGM). In this regard, at first, acceleration response spectra of rotational components are estimated and compared with translational ones. Next, by determining the effective structural parameters in earthquake rotational loading, new methods in order to consider the effects of the rotational components in seismic codes are presented. Numerical results show that according to the frequency content of rotational components, the contribution of the rocking components to seismic excitation of tall and stiff structures can never be ignored. During strong earthquakes, these rotational motions may lead to unexpected overturning or local structural damages for structures located on soft soil. The structural irregularities along the height of the buildings are not strongly influential on the seismic loading of the rocking components. Also, arrangement of lateral-load resisting system in the plan can severely change dynamic behavior of the wide symmetric buildings under earthquake torsional excitations.

Free field rotations: relevance on buildings in near field

Alberto Castellani, *Roberto Guidotti*
Politecnico di Milano, Italy

Tuesday, October 12th, **10:20–10:40**

Soil rotations around horizontal axes, during an earthquake, are studied. The relevance of this input motion for relatively tall structures is examined, with reference to the structural effects that the horizontal motion concurrently provide. Meaningful will be ranked those effects of the order of magnitude of 20% or higher than those implied by the horizontal translational excitation.

Rotations, or rotation accelerations, are obtained through cross power spectra of records collected by closely spaced arrays of strong motion accelerometers. For understanding the relevance on building structures, this procedure has two areas of concern: 1) the coherence implicit in the cross power spectra, which depends on the interpolation function used to obtain the cross spectra, and 2) the relative importance of the vertical to the horizontal input motion.

For the first item, three coherence functions suggested by Haricandran and Vanmarke (1984), Luco and Wong (1986), and Abrahanson et al. (1991), are compared. The coherence developed by the first Authors provides in general meaningful rotations, while that of Luco and Wong, provides meaningless rotations, for the example of relatively tall building examined in the application. Coherences developed by Abrahanson et al. offer the most circumstantiated appliance, although it is based on a set of records of a single earthquake.

The relevance on structures largely depends on relative importance of the vertical to the horizontal input motion. With reference to the horizontal motions, Eurocode 8 establishes unimportant vertical motions at low frequency, and in consequence soil rotation is of little concern, i.e. the effects are of the order of the uncertainties invariably associated to earthquake effects. However, if comparable vertical and horizontal accelerations are assumed for the input motion, as it appears in most records collected in the near field, rotations can provide meaningful contribution to stresses and displacements. Rotation response spectra are built up to provide a measure to rotations.

Results obtained through the present procedure are in good agreement with the richest set of experimental data so far available, published by Liu et al, 2009.

Rotation accelerations are centered in a range of frequencies above 5-10 Hz. The high frequency content of the response spectrum has little effects in most engineering applications. Meanwhile it is the low frequency content of the response spectrum that largely depends on the interpolation function used to obtain the cross power spectra, and on the response spectrum for vertical acceleration.

In the literature the spatial distribution of the ground motion at the free-field surface during an earthquake has been described through several quantities: the ensemble of translation measurements obtained by closely-spaced arrays of instruments, the cross power spectra elaborated on such an ensemble, the rotation at a point obtained by apposite instruments, the average rotation between two separate points laying on the surface.

Previous evaluations of rotational ground motion have been based on records of translational motions and wave propagation theory. Accelerograms recorded at some tens of km from the source were used. When a distinction between wave types is possible, wave theory provides a picture of the propagation pattern around the recording station.

Local vibration of beams and columns, without important motion of the building center of mass, is promoted by the high frequency content of the rotation motion. Overturning motion, involving horizontal displacement of the center of mass, is provided by the low frequency content, at frequencies around the first natural frequency of the building. In terms of stress in structural elements, the second effect appears to be more important. We have attempted a similar goal numerically with finite element techniques, Stupazzini et al. 2009.

Tilt Errors on Recorded Accelerations from Instrumented Structures

E. Kalkan[1], *V. Graizer*[2]

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[2] U.S. Nuclear Regulatory Commission, USA

Tuesday, October 12th, **11:10–11:30**

Modern strong motion recording sensors rely on highly damped (mass-on-rod) pendulum system in which mass moves in a horizontal or vertical plane. This type of sensor is intended to measure ground motion in one of three orthogonal directions, yet it is also sensitive to rotations. Few degrees change in sensitivity plane of a sensor oriented to record translational motion may create additional inertial force acting on its mass due to gravity. Thus, mass of pendulum starts responding not only to translational ground motion but also to tilt and gravitational acceleration. Such coupled response is less pronounced for sensors recording vertical motion due to their specific orientation. Although rotations due to ground shaking are in general small at ground surface, they can easily exceed few degrees in structures due to foundation rocking, structural response or combination of both. Formation of plastic hinges and associated chord rotations in bridge bents, cumulative drifts in shear-beam type structures or flexible diaphragms in regular buildings can potentially create notable rotations on structures that can contaminate recorded translational motions. This contamination manifests itself as long period waves and baseline shift in acceleration time histories. By filtering out low frequencies, it becomes impossible to get true displacements (both dynamic and residual) after double time integration of processed acceleration record.

In this study we are using recordings of the 1992 M 7.3 Landers earthquakes at the instrumented bridge bent in California to calculate rotations. This bridge bent is taken as a proxy to identify the level of error in recorded motions at the superstructure level by ignoring tilting of sensors due to structural and/or foundation response. It is demonstrated that special correction to raw data is needed to recover the true translational motion from a record contaminated by tilt.

The Effect of Rocking Component of Strong Ground Motion on the Structural Response

Gholam Reza Nouri
University of Mohaghegh Ardabili, Iran

Tuesday, October 12th, **11:30–11:50**

In traditional earthquake engineering, structures are designed to resist only simplified representation of strong ground motion, in terms of three translational components of ground motion. The rotational components are almost ignored in design or assessment of engineering structures due to lack of recorded motions. Rotational component of seismic strong motion is attracting attention because of its influence on the overall response of structures. The previous studies were indicated that the effect of rocking component can be considerable especially in near field earthquakes. In this paper the effect of rocking component on the structural response is studied. The structures are modelled as single degree of freedom (SDOF) oscillator with varying structural parameters such as height and ductility. The data of Chiba dense array and geodetic method are employed to estimate the rocking ground motion from translational component. Elastic and inelastic analyses are performed on the models for two excitation cases: (1) rocking and translational components acting simultaneously and (2) only translational component. Comparing the dynamic response of the system for these two loading cases will be introduced as the effect of rocking component. The results show that, the response of structures was increased by including the rocking excitation. This influence is more considerable in tall and ductile structures.

Nonlinear isotropic elastic reduced Cosserat continuum as a possible model for geomedium. Spherical presstressed state.

Elena Grekova

University of Seville / Institute for Problems in Mechanical Engineering of Russian Academy of Sciences, Russia

Tuesday, October 12th, **13:30–14:00**

There are many experimental evidences of existence of rotational degrees of freedom in geodynamics on different scales: vortex structures, rotations of blocks of geomedium, shear-rotational motions in earthquakes in the near field, large rotations of inhomogeneities on the Earth surface caused by earthquake. We suggest a nonlinear elastic reduced Cosserat continuum as a possible model to describe this kind of phenomena.

In this model, each particle can perform large rotations and translations. Rotations are kinematically independent on translations. Reduced Cosserat continuum does not react to the gradient of rotation, but resists to the rotation of each particle relatively to the background medium. Therefore, the stress tensor, generally speaking, is not symmetric, but the couple stress tensor is zero.

We obtain constitutive and dynamic equations of an elastic reduced Cosserat continuum and consider small deviations from a nonlinear spherical stress state, reached quasistatically from the natural state. We show that for a wide class of homogeneous isotropic elastic reduced Cosserat continua the material fails under large pressure (the mechanism of failure is via shear perturbations at rather low frequencies) as well as under large tension (the mechanism of failure is via rotational perturbations at rather high frequencies). In the zone of stability, the material behaves as a linear isotropic reduced elastic Cosserat continuum, suggested for the first time by Schwartz, Johnson, and Feng to describe soils and investigated in works by Grekova, Kulesh, and Herman. At low frequencies, and for high frequencies if the elastic parameters satisfy a certain condition, this material behaves as a classical elastic medium. However, there is a domain of frequencies where the material behaviour is strongly influenced by existence of rotational degrees of freedom. In this domain the rotational and shear wave are strongly coupled, and there is a strong dispersion and apparent attenuation. There is a special resonant frequency, at which particles of the medium perform rotational motions like a large system of decoupled rotational penduli. Below this frequency, there is a forbidden zone of frequencies where a shear-rotational wave does not exist. Green functions for harmonic point sources show that in this forbidden zone a part of the wave is localised near the source. If infinitesimal heterogeneities in density and inertia tensor are present, and the frequency of the shear-rotational incident wave lies in the forbidden zone, this wave is localised at heterogeneities. Rayleigh-type wave has similar peculiarities: existence of a forbidden zone of frequencies, existence of both cut-off frequency and cut-off wave number, polarization, and localisation phenomena.

The aim of this work, done in terms of rational mechanics and based on the fundamental laws of balance, is to show some properties of the nonlinear reduced Cosserat continuum and let the community of geoscientists to judge if this model can describe some experimental data.

Measurements of translation, rotation and strain: New approaches to seismic processing and inversion

Moritz Bernauer
LMU Munich, Germany

Tuesday, October 12th, **14:00–14:20**

We propose to include measurements of seismically induced rotation and strain in tomographic inversions for 3D Earth structure, thus going beyond standard seismic tomography that is based exclusively on recordings of translational ground motion. Exploiting more than 3 observables is expected to yield more detailed tomographic images.

To find efficient inversion schemes based on subsets of the 12-component recordings, we first investigate the sensitivity of the new observables with respect to Earth structure. For this we combine spectral-element simulations of seismic wave propagation and adjoint techniques, that allow us to calculate sensitivity kernels for all 12 observables with respect to the P and the S velocities.

In order to construct sensitivity distributions with pre-defined properties, we combine different observables, thus inventing new types of measurements: The ratio of the rms displacement velocity and the rms rotation, for instance, defines an apparent S velocity that is sensitive only to the true S velocity in the vicinity of the receiver. Similarly, the sensitivity to the true P velocity of the apparent P velocity defined as the ratio of the rms displacement velocity and the rms divergence, is also restricted to the near-receiver region. This behaviour is in sharp contrast to the sensitivities of travel times or amplitudes that are nonzero within a large volume around the entire ray path.

Our systematic study of sensitivity distributions for the apparent S velocity and the apparent P velocity reveals that both measurements have the potential to contribute valuable information in local tomographic studies that are based on teleseismic data.

Observations of Long-Period Rotational Ground Motions: From ambient noise to Earth's Free Oscillations

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Tuesday, October 12th, **14:20–14:40**

After some technical improvements to the ring laser system measuring the vertical component of rotation rate at Wettzell, Germany, in 2009, a marked improvement of the signal-to-noise ratio for the broad-band frequency range of seismic observations could be achieved. This led to the first direct observation of rotational ground motions induced by toroidal free oscillations of the Earth, following the $M_W = 8.1$ Samoa earthquake on September 29, 2009 and the $M_W = 8.8$ Chile earthquake on February 27, 2010. Seismograms are compared with synthetic seismograms computed by summing normal modes. Amplitude spectra of real and synthetic data are analyzed to interpret the observations. We show that several toroidal modes can be detected in the ring laser data and that our observations are in reasonable agreement with the synthetic spectra. This indicates that long-period seismology can benefit from measurements of rotational ground motion measurements using ring lasers in the future. In addition, analysis of earthquake-free time windows of the ring laser records leads us to the conclusion that we consistently observe Lovewaves generated in the two ocean-generated microseismic frequency bands and that the azimuth of the source areas can be estimated from joint analysis with translation records from a broadband seismometer.

Inverting Ground Motion from a Seismometer Array to obtain the Vertical Component of Rotation: A Test Using Data from Explosions

W. Chi[1], *W. Lee*[2], *C. Lin*[1], *J. Aston*[1], *and C. Liu*[1]

[1] Academia Sinica, Taiwan

[2] U.S. Geological Survey, USA

Tuesday, October 12th, **14:40–15:00**

We study what affects the reliability of deriving rotational ground motions using translational array waveforms. The dataset was collected when explosives were set off about 500 m away from a specially designed seismic array in free field consisting of 8 tri-axial rotational sensors and 13 tri-axial accelerometers. We recovered the first order features of vertical rotational ground motions in the 0.5 to 20 Hz bandwidth using the Spudich and Fletcher's procedure (2009). We also formulated a different way of inverting the translational waveform data using the Jaeger's (1969) formula and derived similar results. However, the synthetics have high standard deviations, possibly due to break down of the rigid body rotation assumptions, as the inverted strains are as large as $5 \cdot 10^{-4}$. Noisy translational data can also contribute 25 % of the standard deviation, based on synthetics waveform tests. We used a station configuration of a dense, small-aperture, translational array combined with a few large-offset stations. A small-aperture array fulfills the uniform rotation assumption in the theory. However, inverting data from such an array requires very accurately recorded waveforms; since waveforms from adjacent stations are very similar. In this case, large-offset translation stations

provide additional constraints in time and space. The inverted results are of good quality for predicting the complete 3-component translational ground motions, even though only horizontal components were used in the inversion. Lessons learned from this study might be helpful for future studies using translational ground motions to derive dynamic ground strains, tilts, and torsions.

Back Calculation of Earthquake-Rotated Objects (EROs)

Klaus-G. Hinzen
Cologne University, Germany

Tuesday, October 12th, **15:00–15:20**

Seismologists have long utilized descriptions of earthquake-rotated objects (EROs) to analyze strong earthquakes. Mallet documented several such objects after the 1857 Neapolitan earthquake. In archaeoseismology, the rotated objects themselves constitute a basis for hypothesizing earthquake ground motions as the driving mechanism for the rotations. However, in practice, usually very little is known about the causing mechanisms. Are rotational ground motions involved, or are pure translational motions with the suitable frequency content and phase relation between the three components sufficient to explain EROs? Can observed rotations help to back calculate the ground motion parameters?

We use a 3D discrete element model of a simple rectangular block resting on a plane surface to study rotation-accompanied rocking. Single sinusoid and Morlet wavelets are used as ground motion input. The amplitude and phase relations between two rectangular horizontal components of the ground motion are systematically varied over a large parameter range, while the ground is fixed in the vertical direction. For a square block with 0.5 m width and 3.0 m height and a 1.0 Hz Morlet excitation function, a threshold of ground acceleration exists at 0.9 m/s^2 below which no rotation is observed. Above this threshold, rocking of the block begins, and the block is progressively rotated up to 1.5 rad depending on the amplitude of the second component of ground motion. The rotational behavior using a single sinusoid is similar. Measured translational strong ground motion from the 2009 l'Aquila earthquake also leads to rotations of the test block around its vertical axis of up to 0.5 rad.

These initial simple numerical experiments show that a slender block can become an ERO without the additions of rotational components of ground motion: however, these effects still need to be calculated.

Research on Rotational Components of Ground Motion in Wenchuan earthquake

Q. Luo, Z. Hong and C. He
Tongji University, China

Wednesday, October 13th, **9:00–9:20**

This paper figures out the apparent wave velocity curves matching Sichuan area based on the records of Wenchuan earthquake, Ms8.0, in 2008, taking into account the frequency dispersion effects on the equivalent group wave speed of seismic wave and the incident angle of the body wave. And then the rotational components of ground motions in Sichuan area are studied, which are further used to discuss the attenuation characteristics and their power spectrum in the region.

Torsional motion due to small-scale geological irregularity

M. R. Ghayamghamian
International Institute of Earthquake Engineering and Seismology, IIEES, Iran

Wednesday, October 13th, **9:20–9:40**

The large variation in ground motions due to large and/or small scale basin-shape geological irregularities may introduce large amplitude rotational ground motions at the sites in the vicinity of basin edge. In this paper, the characteristics of rotational ground motions generated by small-scale basin were investigated. To this end, the small-scale basin was modeled using 2-D FLIP computer program. The surface motion at different positions with respect to basin edge was simulated by subjecting to an earthquake motion at engineering bedrock (shear wave velocity of 600-800 m/s). Then, the torsional ground motion was estimated from translational components between two adjacent sites. The results revealed that the torsional ground motion in the vicinity of basin edge show a large amplitude because of shear wave coupling between two shear waves propagating in different geological conditions at two sides of basin edge.

Using the Wavelet Transform to Estimate Instantaneous Tilts

A. Chanerley, N. A. Alexander
University of East London, UK

Wednesday, October 13th, **9:40–10:00**

The wavelet transform has been found useful in obtaining low-frequency fling profiles from seismic events. The method uses the transform in order to separate the accelerometer time series into low and high frequency sub-bands. This makes it easier to automatically correct for baseline offset and re-integrate down to obtain estimates of one and two-sided velocity pulses and displacement. Furthermore the method lends itself to obtaining estimates of the mean values of tilts/rotations from the low-frequency fling, using least squares. These estimates were found to be of the order of 10-4 radians. Moreover it was also found that the baseline offset in the velocity had been initiated by a transient in the acceleration giving a tilt angle of the order of 10-3 radians. The resulting acceleration, velocity and displacement profiles are in line with the work of other researchers, experimenting with accelerometers and subjecting them to various tilt profiles. The paper discusses the results obtained from the Chi-Chi events (1999) as well as from more recent events in Iceland (2008).