42. Effects of torsional and rocking excitations on the response of structures

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42.1 Introduction

In traditional earthquake engineering, structures are designed to resist only simplified representation of strong earthquake ground motion, in terms of the horizontal translational components of acceleration. Occasionally, in the design of important structures with long spans, the vertical component of excitation is also considered. Rotational excitation by the torsional and rocking components of strong ground motion is almost never considered. The significance of the rotational components of strong motion for the overall response of structures can be evaluated using analytical solutions of the soil-structure interaction problems, by means of numerical modeling, or with probabilistic representations of response. At present, there are only a few isolated recordings of the rotational components of strong ground motion, and it is therefore possible only to work with their simulations.

This chapter reviews the methods for construction of artificial torsional and rocking strong motion accelerations, using the theory of linear wave propagation in a layered half space. These motions, along with the corresponding translational components, can be used to evaluate the response of typical structures. Their significance can be evaluated by comparing the responses computed with and without their participation in the general forcing functions.

The generation of seismic waves can be examined from two different views. The first is the classical macroscopic view, which starts with a kinematic representation of faulting (Haskell, 1969) and then follows the radiated elastic waves using the first-order linear theory of elasticity. If nonlinear phenomena occur along the wave path, and if those are investigated, the analysis is usually restricted to the response of soft soil deposits near the ground surface. The second view involves the microphysics of fracture in rocks and includes the irreversible deformations from dislocations, disclinations and micro cracks (Teisseyre and Majewski, 2002). In the following review of the effects of rotational strong ground motion on the response of man-made structures, only the first, macroscopic representation will be considered.

Rotational ground motions accompanying seismic waves and their effects on simple objects (obelisks, grave stones) and buildings are mentioned in many older texts, which by describing the consequences of strong shaking aim to decipher its physical nature (Hobbs, 1907; Davison, 1927; Gutenberg, 1927; Richter, 1958; Imamura, 1937). Deployment of strong motion accelerographs in many seismic areas of the world during the past seventy years has produced data on translational components of motion during many strong earthquakes. This data describes strong motion in three orthogonal directions (two horizontal and one vertical), but because the spacing of the recording sites is much larger than the wavelengths of the recorded motions, little is known today about the accompanying differential and rotational motions.

The effects of differential motions on man-made structures include strains (Lee, 1990), curvatures (Trifunac, 1990), torsion (Newmark, 1969; Luco, 1976; Scanlan, 1976; Lee and Trifunac, 1985) and rocking excitation (Lee and Trifunac, 1987) of foundations, which, for flexible, extended, multiple and separate foundations (e.g. bridges) can lead to large pseudo-static shears and moments (Trifunac and Todorovska, 1997a). Many structural failures and much of the damage caused by earthquakes have been linked to differential and rotational ground motions. Hart et al., (1975) showed that large torsional responses of tall buildings in Los Angeles, during the San Fernando, California earthquake in 1971, could be ascribed to torsional excitation, while longitudinal differential motions may have caused the collapse of bridges during San Fernando 1971, Miyagi-ken-Oki 1978 (Bycroft, 1980) and Northridge 1994 (Trifunac et al., 1996) earthquakes. Earthquake damage to pipelines that is not associated with faulting or landslides but is due to large differential motions and strains in the soil reflects the consequences of traveling seismic waves and of the associated large rotations and twisting of soil blocks caused by lateral spreads and early stages of liquefaction (Ariman and Muleski, 1981; Trifunac and Todorovska, 1997b; 1998; Trifunac, 1997; 2003).

Studies of the rotational components of strong motion and of their effects on man-made structures are relatively young. Much can be anticipated and studied theoretically, but our understanding of these motions will gain sound and realistic basis only when a large number of recorded rotational accelerograms becomes available. This may take several decades and will require deployment of a large number of new strong motion instruments that will record all six components of motion (three translations and three rotations; Trifunac and Todorovska, 2001a,b).

42.2 Rotational Strong Ground Motion

In linear elastic media, the rotations are expressed as space derivatives of the displacements. Other contributions to rotational motion result from the internal structure of the medium, non-symmetric processes of fracture, and friction (Teisseyre et al., 2003). However, once generated, these additional rotational motions are believed to attenuate quickly, and so, to be studied experimentally, they have to be recorded in the near field (Teisseyre, 2002; Teisseyre and Boratynski, 2002).

During the past thirty years, the inversion of recorded strong ground motion (Trifunac, 1974; Trifunac and Udwadia, 1974; Jordanovski and Todorovska, 2002) has been developed to such a degree that it now can describe spatial and temporal variations of slip on the fault surface. Many inverse studies of the source mechanism have shown that the distribution of slip can be very irregular (Jordanovski and Todorovska, 2002). Along the edges of fault planes and near abrupt changes of fault slip, tensile fractures can contribute to the radiation of rotational waves (Takeo and Ito, 1997). Through comparison of computed and recorded rotational velocity during an earthquake swarm in March 1997 off the shore of Izu peninsula in Japan, Takeo (1998) showed that the recorded rotations were several times larger than the simulated rotations computed from linear displacements excited by dislocations on the fault (Bouchon and Aki, 1982). He showed that the agreement between the recorded and simulated rotations can be improved if "direct excitation of rotational motions due to spatial variations of slip velocity and due to rotational strains" is added to the rotations excited by dislocations alone.

Translational and rotational components of strong motion radiated from an earthquake source are modified along the propagation path through interference, focusing, scattering, and diffraction. For example, reflection of plane P and SV waves from a half space can lead to large displacement amplitudes for incident angles between 30° and 43°, but the associated rotations (rocking for P and SV waves, and torsion for SH waves) change monotonically and do not lead to large amplifications (Trifunac, 1982; Lin et al. 2001). Scattering and diffraction of plane waves from topographic features can lead to focusing and to amplification for both displacements and rotations (Sanchez-Sesma et al., 2002).

Beyond the results of linear theory, in the near field, the non-linear response of soil and ultimately soil failure and liquefaction can lead to large transient and permanent rotations. Four types of ground failure can follow liquefaction: lateral spreading, ground oscillations, flow failure, and loss of bearing strength. *Lateral spreads* involve displacements of surface blocks of sediment facilitated by liquefaction in a subsurface layer. This type of failure may occur on slopes up to 3° and is 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 (e.g., at Seward and Valdez during the 1964 Alaska earthquake; Trifunac and Todorovska, 2003). *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 rotations, which so far have been neither evaluated through simulation nor recorded by strong motion instruments.

42.3 Recording Rotational Strong Motion

Direct instrumental data on rotational components of earthquake ground motion (Farrell, 1969; Shibata et al., 1976; Teisseyre et al., 2003; Takeo, 1998) and of the motions in the vicinity of large explosions (Nigbor, 1994) are rare. This can be attributed to two factors. The first factor is that in traditional seismology, the recorded motions are small, because of the large epicentral distances, and thus the recording of the associated rotations has received little attention. The second factor is that it is more difficult to design transducers to measure rotations (Graizer, 1989). Following the development of strong motion accelerographs since the 1930s, which was influenced by the experiences with the design of seismological transducers, it is now becoming clear that for complete characterization of strong motion—and in particular for computation of permanent displacements following earthquakes—in the near-field, all three translational and three rotational motions must be recorded (Trifunac and Todorovska, 2001b).

Stedman et al., (1995) observed, using a ring laser gyro, torsional ground motion excited by a magnitude 6.3 earthquake in New Zealand, at epicentral distance of 200 km. Other ring laser interferometers (gyroscopes with zero inertial moment) for recording angular motion are described in Takeo and Ito (1997), Jaroszewicz et al., (2001) and Cochard et al., (2003).

Takeo (1998) described and analyzed three translational and three rotational components of ground velocity recorded during two earthquakes offshore of Ito on Izu peninsula, Japan, in 1997. He measured rotational motions with Systron Donner triaxial gyro sensors, with a full-scale output capacity of 8.7×10^{-1} rad/s and with flat frequency response from 0 to 75 Hz.

A rotational seismograph consisting of two penduli with opposite orientations and with identical mechanical properties (Graizer, 1989; Moriya and Marumo, 1998) in Ojcow Observatory, Poland, recorded a small Silezian earthquake event of magnitude 1.5 at an epicentral distance of about 60 km, on 11 July, 2001 (Teisseyre et al., 2003). So far, nobody has succeeded in recording strong rotational motion in the near field of large earthquakes.

The average "rotational motions" can be approximated from the difference of two translational records in an array of stations on the ground (Huang, 2003; Castellani and Boffi, 1986, 1989; Oliveira and Bolt, 1989; Nathan and MacKenzie, 1975; Droste and Teisseyre, 1976) and in structures (Moslem and Trifunac, 1986; Trifunac and Todorovska, 2001c; Trifunac and Ivanovic, 2003). Such estimates, in principle, will approximate the rotations at a point only for wave-lengths much longer than the separation distance. This is a limitation for the studies of rotational strong motion in the ground and in flexible foundations of structures (Trifunac et al., 1999; Trifunac and Todorovska, 2001c), but this approach is suitable and desirable in engineering analyses of the responses of buildings in terms of inter-story drifts (Trifunac and Ivanovic, 2003).

42.4 Generation of Synthetic Rotational Motions

In the following, it is assumed that the x_1-axis coincides with the radial coordinate, and lies in the plane containing the earthquake source and the recording station. The x_3-axis is perpendicular to this plane and coincides with the transverse direction relative to the earthquake source. The vertical coordinate, x_2, is perpendicular to the surface of the half space. Then, in elastic, isotropic, and layered half space, P, SV, and Rayleigh waves will produce only horizontal (x_1), vertical (x_2), and rocking φ_{x_3} (about the x_3 axis) motions, while SH and Love waves will produce only transverse (x_3) and torsional φ_{x_2} (about the x_2 axis) motions.

An early engineering suggestion, that torsional ground motion occurs during strong earthquake ground motion, may have been made by Rosenblueth (1957). The first proposal on how this torsional excitation could be estimated was made by Newmark (1969), who assumed that the apparent velocities of strong motion can be approximated by one equivalent velocity, c, for all frequencies of transverse motion. Newmark's idea was adopted and further explored in the studies of Nathan and MacKenzie (1975), Morgan et al., (1983), Awad and Humar (1983), and Rutenberg and Heidebrecht (1985). Through spectral analyses of the responses of tall buildings during the 1971 San Fernando earthquake in California, Hart et al., (1975) showed that torsional motions can indeed contribute significantly to the overall response. Their study was limited by the fact that there was only one strong motion accelerograph on the roof of each building, which prevented them from quantitatively separating out the torsional contributions to the response. With the introduction in the mid-1970s of central recording systems with distributed one-channel recorders throughout the buildings, this limitation was partly eliminated (e.g. Kojic et al., 1984; Trifunac and Ivanovic, 2003).

Analyses showing that the rocking response of structures is caused not only by the compliance of the soil during soil-structure interaction but also by the rocking of foundations caused by the passage of P, SV, and Rayleigh waves started to appear in the earthquake engineering literature in the mid-1980s (Castellani and Bofi, 1986, 1989; Lee and Trifunac, 1987). Many analytical studies showed the significance of those rocking excitations for continuous (e.g., Todorovska and Trifunac, 1990a,b; 1992a,b) and for base isolated structures (Todorovska and Trifunac, 1993), but during the past 20 years the studies of rocking excitation have been outnumbered by the studies of torsional excitation and response. Proper separation of the effects of rocking excitation and the rocking associated with soil-structure interaction are essential for interpretation of the observed inter-story drifts in full-scale structures. However, with the current instrumentation in tall buildings, which typically consists only of translational transducers, this separation cannot be carried out even approximately (Trifunac et al., 2001a,b,c; Trifunac and Ivanovic, 2003). For buildings with large floor plans, warping and deformation of the foundation (Trifunac et al., 1999; Hayir et al., 2001; Todorovska et al., 2001), differential translational, and rocking seismic waves further complicate both analysis and recording of the response of full-scale structures. Further work needs to be done in this area before the role of rocking excitation can be understood and then included in engineering design.

In the absence of recorded rotational components of strong motion, it is important for engineering studies of response to have at least preliminary and physically realistic simulations of such motions. At present, the method of Lee and Trifunac (1985, 1987) for generation of artificial torsional and rocking accelerograms meets most of these requirements. This method is an exact analytical method, if it is accepted that (1) the motion occurs in linear elastic, layered half space, and (2) that synthetic ground motion can be constructed by superposition of body P and SV and surface Rayleigh waves for rocking (Lee and Trifunac, 1987), and by body SH and surface Love waves for torsion (Lee and Trifunac, 1985). This method has been extended to predict the associated strains (Lee, 1990) and curvatures near the surface over time (Trifunac, 1990) during the passage of seismic waves.

The synthesis of translational motions is based on the procedure proposed by Trifunac (1971) and later refined by Wong and Trifunac (1979). This procedure generates random, transient time series data, with arrival times determined by the empirical travel times of P and S waves in the area and by computed arrivals of surface waves determined from phase and group velocities in the layered structure. After random time series have been created, their amplitudes are scaled to produce correct (desired) Fourier (or response) spectrum amplitudes, based on empirical scaling laws in terms of earthquake magnitude, distance, and local soil and geologic site conditions (e.g., Lee 2002a). At the end, the frequency-dependent duration of each random time series is modified to agree with empirical estimates of the duration of strong motion in terms of selected empirical scaling equations for duration of strong motion (e.g., Lee 2002b). Because in this process all characteristics of the incident body and surface waves are known, those can be used for the computation of rotations, strains, and curvograms (Lee, 2002c).

42.5 Response of Structures

The computation of the dynamic response of a structure to earthquake shaking requires specification of the forcing function and of the mathematical model of the structure. How close the result will be to the actual response can be determined only by full scale experiments, preferably through a comparison with recorded response during earthquake shaking. In traditional earthquake engineering, only one or two translational horizontal components of strong motion acceleration are used as forcing functions. The vertical accelerations are usually neglected, because the methods of solution are formulated assuming small deflections. The combined effects of vertical, rocking, and torsional accelerations cannot be neglected in the computation of response of bridge structures (e.g., Werner et al., 1979). However, most earthquake engineering calculations of response do not consider the effects of gravity and vertical accelerations, and by adopting these simplifying assumptions ignore the consequences of dynamic instability (Lee, 1979). Because both are significant during the collapsing stage of response, for a typical selection of forcing functions, a meaningful prediction of response is possible only for relatively small response amplitudes. The excitation by rotational components of strong motion (torsion and rocking) is also usually ignored. Some analytical studies do include torsional excitation (Luco, 1976; Todorovska et al., 1988), but explicit consideration of rocking excitation is very rare.

An elementary representation of simple structural systems is often based on a model with a rigid foundation slab supporting a one-dimensional set of lumped masses interconnected by massless springs, and with dashpots to simulate local dissipation of vibrational energy. Such models have been used to analyze elementary consequences of soil-structure interaction and are common in many studies and applications of the Response Spectrum Method (Biot, 1942; Trifunac, 2002; Gupta and Trifunac, 1987a; 1990a). These models have also been studied and used in some detail to evaluate the significance of the effects of torsional excitation (Gupta and Trifunac, 1987b; 1989; 1990c) and of rocking excitation (Gupta and Trifunac, 1988a, 1990b, 1991). By using order statistics of the peaks in earthquake response (Gupta and Trifunac, 1988b), the contribution of torsional and rocking excitation has been characterized in terms of tens of the largest peaks of response, not just the largest peak, which forms the basis for the Response Spectrum Method. These studies have shown how significant torsional and rocking excitations can be, and for what combinations of structural and soil properties. It has been shown, for example, that rocking excitation becomes important for tall structures supported by soft soil deposits, while torsional excitations can dominate in the response of long and stiff structures supported by soft soils.

Some observations of the response of buildings during earthquake shaking have lead to similar findings. For a seven-story, symmetric, reinforced concrete structure, for example, which was damaged in 1971 by the San Fernando Earthquake and again in 1994 by the Northridge earthquake, the torsional response contributed up to 40 percent to the motion at the roof (Trifunac and Ivanovic, 2003). Coupled with the non-linear response of soils and large excentricities in soil-structure interaction, torsional and rocking excitations of ground motion contributed to significant damage to this building (Trifunac et al., 2001b,c). In another well-studied building (Hollywood Storage building) in Los Angeles, asymmetry of the foundation and strong torsional excitation by surface waves propagating essentially along the longitudinal axis of the building resulted in large torsional response (Trifunac et al., 2001a).

Recording, analysis, and interpretation of the contributions of torsional and rocking excitations to the total inter-story drifts in structures are also essential for future development of earthquake-resistant design codes. Without proper consideration of these contributions, the observed drifts may be erroneously assumed to result completely from relative displacement of structures, and this can lead to false confidence that the current design methods are "conservative" (Trifunac and Ivanovic, 2003).

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