Engineering Structures 155 (2018) 387–393

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Time history response analysis of a slender tower under translational-rocking seismic excitations

Bońkowski Piotr Adam[a,*], Zembaty Zbigniew[a], Minch Maciej Yan[b]

[a] Opole University of Technology, Poland
[b] Wroclaw University of Science and Technology, Poland

ARTICLE INFO

Keywords:
Rotational component
Time history analysis
Seismic analysis
Structural response
Slender towers
Chimneys

ABSTRACT

Two records from 6-dof ground motion monitoring of induced seismic events are applied to study seismic response of a slender tower under horizontal-rotational excitations. The response of 160 m reinforced concrete, industrial chimney is investigated under moderately intensive, simultaneously acting translational-horizontal and rocking components of the ground motion (rotation about horizontal axis). Time history response analysis shows substantial contribution of rotational excitations in the flexural vibrations of the chimney: 18% in the upper part and 65% at the base. The paper demonstrates that overall response of slender towers can effectively be studied only by using credible, 6-dof seismic records because of the important role of interaction of horizontal and rotational excitations, in which frequency contents and proper phases of excitation records play important role in the structural response. Results of such analyses with more and more intensive records are important for future calibrations of seismic design codes using response spectrum approach, as in the case of Eurocode 8, part 6: *Towers, masts and chimneys*.

1. Introduction

In conventional design of slender towers or tall buildings it is the horizontal component of seismic ground motion that is treated as the primary seismic load. For a long time, however, researchers (e.g. Rosenblueth [1], Newmark and Rosenblueth [2], Trifunac [3]) have predicted the presence of additional rotational excitations. Since any point on the ground surface may be subjected to three translations $u(t)$, $v(t)$ and $w(t)$ along x, y and z-axes, respective three rotations can be measured about these axes (Fig. 1). One of the horizontal axes can be directed towards epicenter. Such system of axes was called principal by Penzien and Watabe [4]. This is because respective cross-correlations of the seismic signals were demonstrated by Penzien and Watabe, to hold tensor properties with the transformation of the coordinate system. In Fig. 1 these six components of ground motion are shown on the ground surface. The ground rotations $\psi(t)$ and $\theta(t)$ about horizontal axes x and y are named *rocking*, while the rotation about vertical axis z is called *torsion*. An alternative nomenclature is taken from ship engineering and aeronautics that leads to names *pitch*, *roll* and *yaw* respectively.

Better knowledge of these additional rotational excitations may substantially improve our predictions of seismic vibrations of tall buildings or slender towers and add substantial non-conservative seismic load to design codes (Fig. 2), [5]. Indeed, even small contribution of the rocking excitations about any horizontal axis may dominate the vibrations of a high slender building, additionally magnified by P-Δ effects.

For many years there was no agreement among seismologists with respect to the importance of the rotational seismic effects and their eventual contribution in the overall seismic ground vibrations (see e.g. the footnote in Richter's *Elementary Seismology* [6], where he undermined the importance of rotational ground motions). Initially the rotational seismic effects were analyzed from theoretical perspective [7] and sporadically indirectly observed [8,9], or retrieved from translational records of pendulum seismographs [5,10–12] using sophisticated techniques based on detailed analyses of the response of pendulum systems to seismic excitations [13,14]. Using this method, Graizer retrieved credible rotational seismic record with tilt reaching 3.1° [12]. Recently, measuring techniques matured enough to propose numerous sophisticated sensors for vehicle and aerospace industry (e.g. [15,16]) or in civil engineering to better monitor inter-story drift [17] and bending of beams [18]. Appropriate devices to acquire rotational seismic ground motions were finally developed (e.g. [19]). With substantial successes in collecting small, teleseismic rotations (e.g. [20]) and the publication of special issues of the *Bulletin of the Seismological Society of America* [21] and *Journal of Seismology* [22] the subject of investigating rotational seismic effects was announced as an emerging

* Corresponding author.
E-mail address: p.bonkowski@po.opole.pl (P.A. Bońkowski).

https://doi.org/10.1016/j.engstruct.2017.11.042
Received 19 April 2017; Received in revised form 16 November 2017; Accepted 20 November 2017
0141-0296/

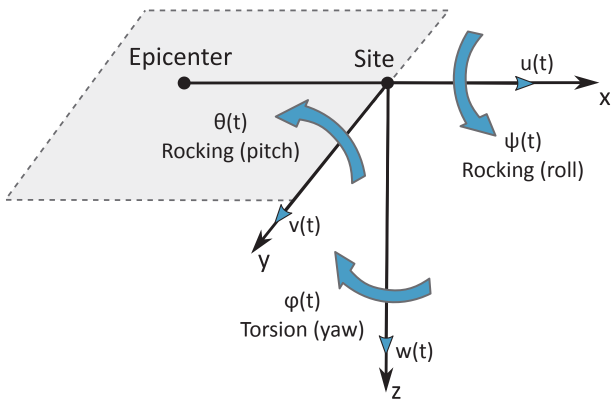

Fig. 1. Configuration of 6 components of surface ground motion.

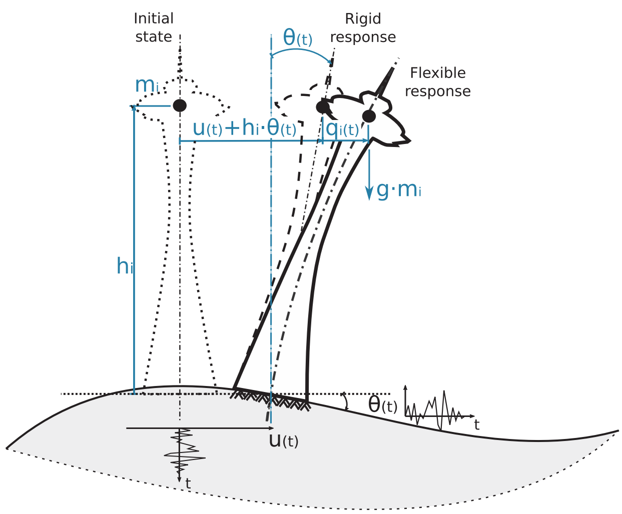

Fig. 2. Sketch of horizontal and rotational ground motion components acting on a high, slender structure.

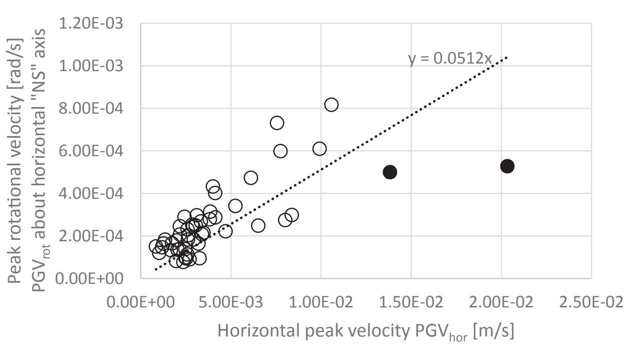

Fig. 3. Peak rotational velocity (PGV_{rot}) versus horizontal spatial peak ground velocity (PGV_{hor}) from measuring program reported by Zembaty et al. [32]. Solid dots stand for records further analyzed in this paper (Table 1).

branch of seismology.

For the purpose of earthquake engineering, one needs however to collect strong rotational records, preferably measured in epicentral areas of major earthquakes. This would require to upgrade numerous existing strong motion stations with properly designed rotational strong motion sensors and wait for major earthquakes with epicenters in close proximity to the stations. Currently, primary activity of seismologists is concentrated on collecting weak, tele-seismic rotational records. For these reasons acquiring good, credible strong rotational signals may still take many years. In the meantime engineers are investigating methods to assess rotational ground motion from studies of the seismic

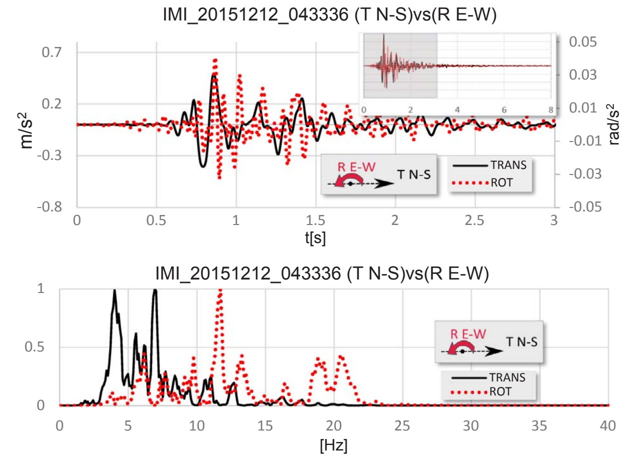

Fig. 4. Ground motion of translational N-S and rotational E-W directions, recorded on December 12th 2015.

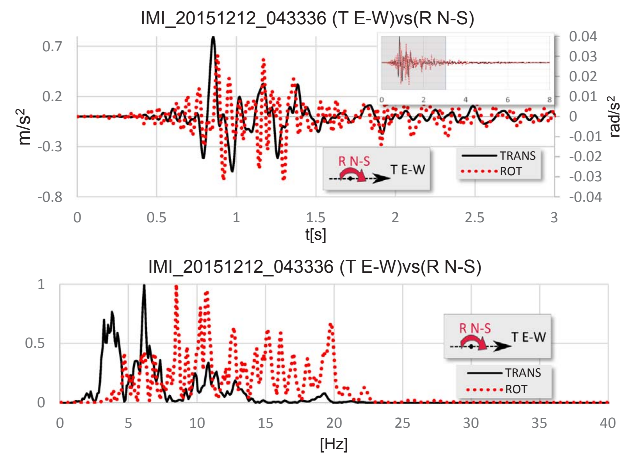

Fig. 5. Ground motion of translational E-W and rotational N-S directions, recorded on December 12th 2015.

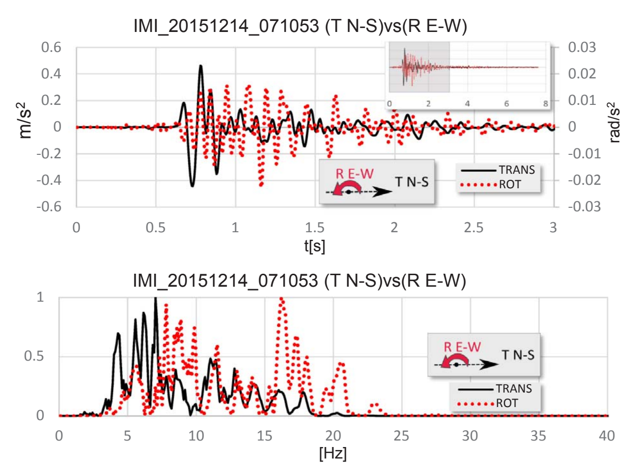

Fig. 6. Ground motion of translational N-S and rotational E-W directions, recorded on December 14th 2015.

wave field ([3]). Such the approach was later continued in numerous, detailed investigations ([23–29]). In order to properly model seismic excitations of tall buildings and slender towers one needs however simultaneous modelling of strong horizontal and rotational seismic effects and the key question arises about the actual proportion of the horizontal to rotational ground motions. Proper verification of any