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SEISMIC RESPONSE OF HIGH AND SLENDER STRUCTURES UNDER TRANSLATIONAL-ROCKING SEISMIC EXCITATIONS

Piotr BOŃKOWSKI[1], Zbigniew ZEMBATY[2], Maciej Y. MINCH[3]

ABSTRACT

This paper presents selected results of time-history seismic response analyses of slender structures under combined horizontal-rocking excitations. An industrial reinforced concrete chimney and a tall building are analysed as the example structures. In contrast to earlier analyses which use theoretical decompositions of seismic wave field to obtain rotations, this study is using 6-dof ground motion records of a moderate intensity with proper phases and signs of the rocking and horizontal seismic components. The analyses of the seismic response to combined horizontal-rocking seismic excitations lead to a conclusion of significant 26-67% contribution of the rotational excitations in the overall structural seismic response.

Keywords: Rotational seismic ground motion; time history analysis; seismic structural response;, slender towers; chimneys

1. INTRODUCTION

In addition to three horizontal components of surface seismic ground motions $u(t)$, $v(t)$ and $w(t)$ along respective axes x, y & z, one may expect also three ground rotations about these axes $\psi(t)$, $\theta(t)$ and $\varphi(t)$ respectively (Figure 1). For decades, the importance or even presence of the rotational ground motion components was disputed among seismologists. When it comes to seismic engineers, it was Rosenblueth (1976) who first postulated their importance and Trifunac (1982) who explained their origin as an effect of wave propagation. For many years it was not possible to directly measure seismic rotations, so various methods emerged to retrieve them from translational records using wave decomposition (e.g. Basu et al., 2013; Falamarz-Sheikhabadi and Ghafory-Ashtiany, 2012; Zembaty, 2009a) or from specific properties of the popular translational recording *SMA* stations (e.g. Graizer, 2009).

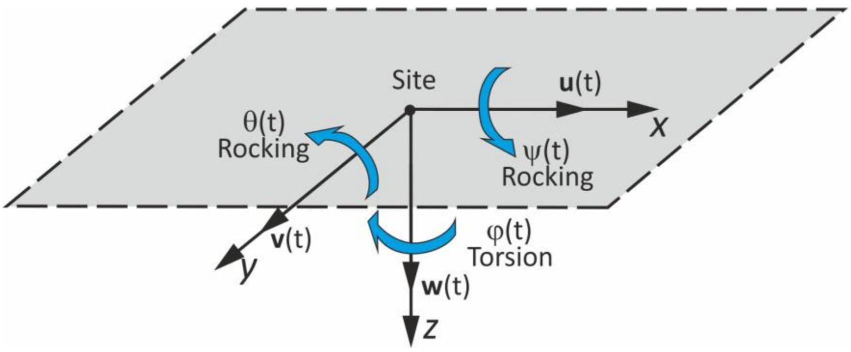

Figure 1. Six components of earthquake ground motion on the ground surface

[1]Opole University of Technology, Opole, Poland, p.bonkowski@po.edu.pl
[2]Opole University of Technology, Opole, Poland, z.zembaty@po.edu.pl
[3]Wrocław University of Science and Technology, Wrocław, Poland, maciej.minch@pwr.edu.pl

Recently new opportunities for measurements appeared and the problem became an emerging research area of seismology (Lee et al., 2009; Igel et al., 2012) with many successful measurements of usually very small, teleseismic 6-dof records. The main problem which remains to be solved is to collect strong motion records important from engineering point of view. Such the rotational ground motions about horizontal axes (rockings $\psi(t)$ & $\theta(t)$ – Figure 1) can dominate structural response of slender towers and tall buildings under seismic excitations. It is believed that the rotational ground rotations can be particularly pronounced for near field ground motion from body waves interacting with free surface (e.g. Zembaty, 2009a) or for far distance surface waves effects (Cakti et al., 2017; Safak et al., 2017).
In what follows moderately strong 6-dof seismic excitations collected from induced seismic events (Zembaty et al., 2017) are applied to compute seismic response of a 160 m high industrial chimney and a 30-story tall building). Having a complete 6-dof record of surface ground motion makes it possible to conclude about contribution of the rotational seismic excitations in the overall, combined rotational/rocking vibrations of the structure which was not possible using previous methods of indirect extraction of the rotational components from seismic wave field. Detailed analysis of the rocking/horizontal seismic vibrations of a slender tower is given it the recent paper by Bonkowski et al. (2018).

2. ROTATIONAL GROUND MOTION FROM INDUCED SEISMIC EVENT

It is obvious that rocking excitations about one axis interacts with horizontal excitations along the perpendicular axis (Figures 1 and 4).
In Figure 2 selected two records of translations along E-W axis and rocking about N-S axis are shown together with their respective Fourier spectra as acquired so far by the recording station located close to *Ziemowit* Mine in Upper Silesia, Poland. This program of recording surface ground motions from induced seismic events is described in detail in recent paper by Zembaty et. al. (2017). With its translational, horizontal PGV=1.4 cm/s (MM intensity about IV) it is one of the most intensive 6-dof records measured so far.

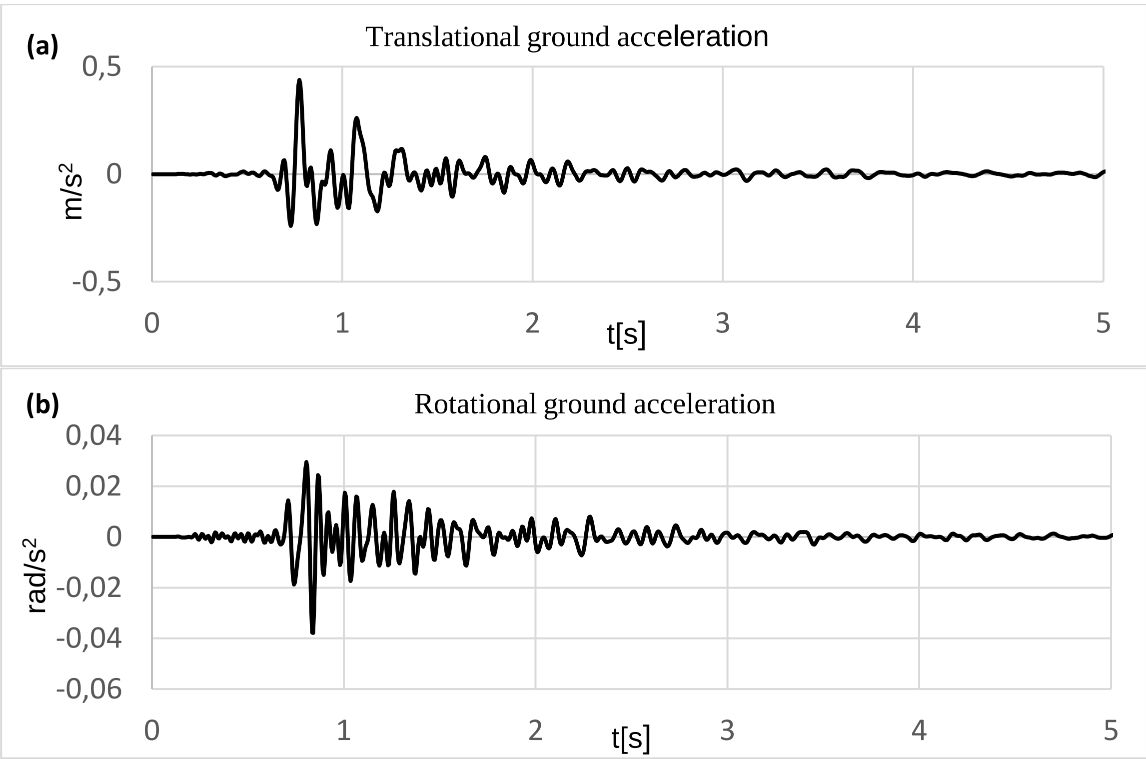

Figure 2. Seismic ground accelerations along E-W axis (a) and respective ground rotational accelerations about N-S axis (b) interacting in seismic vibrations of structures (see Figures 1 and 4)

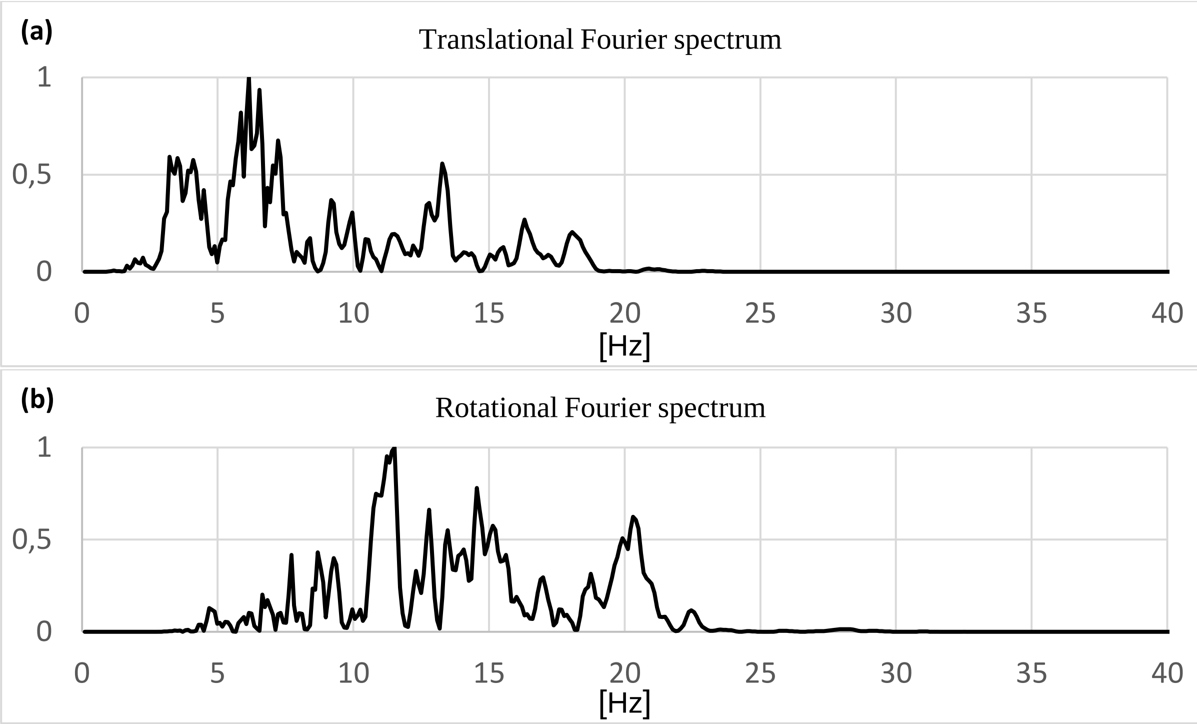

Figure 3. Fourier spectra of seismic acceleration records of translations (a) and rotations (b) from Figure 2.

In Figure 3 Fourier spectra of the seismic records from Figure 2 are shown. Characteristic shift in frequency content predicted by theoretical investigations (e.g. Zembaty, 2009a) can be observed. The seismic records form Figure 2 will be used in computing time history response of structures to combined rocking-horizontal excitations.

3. RESPONSE OF A SLENDER TOWER TO COMBINED TRANSLATIONAL AND ROCKING GROUND MOTION

Consider a high, slender structure under combined translations u(t) and rocking $\theta(t)$ (Figure 4).

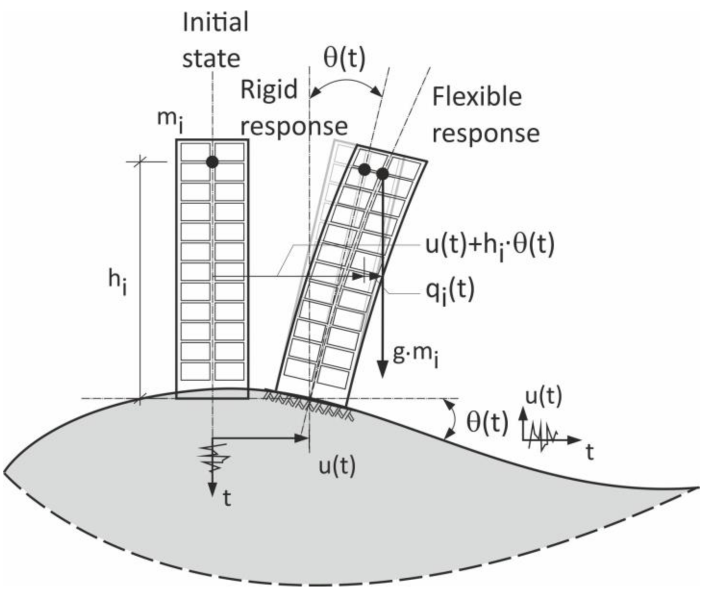

Figure 4. Sketch of a building structure under combined translational-rotational ground motion

The equation of motion of such plane vibrations takes following form:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{C}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = -[\boldsymbol{m}\ddot{u}(t) + (\{\boldsymbol{mh}\})\ddot{\theta}(t)])\} \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are mass, damping and stiffness matrices respectively. $\ddot{\boldsymbol{q}}, = \ddot{\boldsymbol{q}}\ (\boldsymbol{t}),\ \dot{\boldsymbol{q}} = \dot{\boldsymbol{q}}(\boldsymbol{t}), \boldsymbol{q} = \boldsymbol{q}(\boldsymbol{t})$ – are acceleration, velocity and displacement vectors describing degrees of freedom of the structure. $\boldsymbol{m}$ – vector of masses in the horizontal direction of the translational excitation. It coincides with the main diagonal of the mass matrix $\boldsymbol{M}$ if vector $\boldsymbol{u}$ includes only translational displacements along horizontal direction of excitations. Symbol $\{\boldsymbol{mh}\}$ denotes vector consisting of $m_i h_i$ values, where m_i and h_i stand for elements of vectors $\boldsymbol{m}$ and $\boldsymbol{h}$. $\ddot{u}(t)$ – translational, horizontal ground accelerations. $\ddot{\theta}(t)$ – rocking accelerations of the base (rocking about horizontal axis 'y' – Figure 1). $\boldsymbol{h}$ – vector consisting of elevations above ground surface of the respective horizontal structural degrees of freedom.

4. EXAMPLE 1: INDUSTRIAL R/C CHIMNEY

The analyzed structure is a reinforced concrete, industrial chimney, 160 m high with basic data shown in Figure 5. The chimney shaft was modeled using 17 finite linear-elastic elements. Additionally, *P-Δ* effects have been included, however for this level of seismic intensity they were not important.

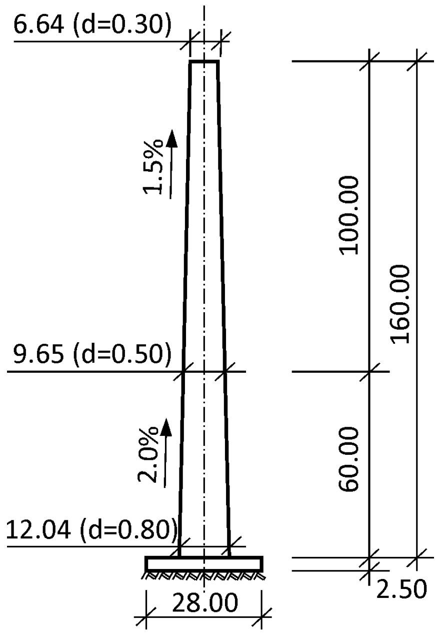

Figure 5. Sketch of the analyzed chimney.

The first four natural periods of the chimney are: 2.80, 0.69, 0.29 and 0.16 s. The two acceleration components of the 6-dof record, as shown in Figure 2: rocking about E-W & horizontal translations along N-S were applied as excitations in a time history integration analysis. As a result dynamic displacement response and bending moments were obtained.

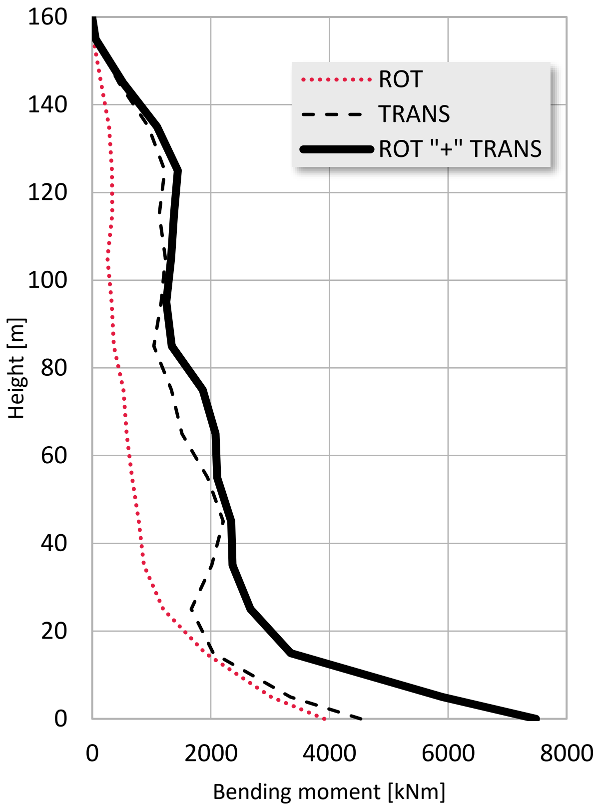

Figure 6. Envelope of bending moments along the height of the chimney (Bońkowski et al., 2018).

When carrying out time-history numerical integrations the horizontal and rocking excitations interact in such a way that their respective phases and signs matter. Such analyses were not possible in previous research of the indirect rotational ground motion effects. In the recent paper by Bonkowski et al. (2018) it was demonstrated that the interaction of signs an phases plays important role in the overall structural seismic response. In Figure 6 envelops of bending moments along the height of the structure (selected from the maxima of the time-history response analyses) are shown for combined rocking-translations and for the translations only. A substantial 67% contribution of bending moments coming from seismic rocking can be observed. The contribution of bending moments in total seismic response is particularly pronounced for the lower part of the chimney.

Table 1. Selected results of time-history seismic analysis of 160 m r/c chimney under combined horizontal-rocking excitations of Figure 2.

Description & Intensity	Bending moment at the base [kNm]			
	Rotation	Translation	Total	Rot Influence
EC8-6 Response Spectrum Method a_g=100 cm/s^2 (Zembaty, 2009b)	2.5E+05	4.8E+05	5.4E+05	13%
Time History Analysis, $PGA_{hor}=64$ cm/s^2, $PGV_{hor}=1.38$ cm/s, IMI_20151214_071053	3.9E+03	4.5E+03	7.5E+03	67%
Description & Intensity	**Bending moment at 2/3 of the total height [kNm]**			
	Rotation	Translation	Total	Rot Influence
EC8-6 Response Spectrum Method a_g=100 cm/s^2 (Zembaty, 2009b)	4.0E+04	6.9E+04	8.0E+04	15%
Time History Analysis, $PGA_{hor}=64$ cm/s^2, $PGV_{hor}=1.38$ cm/s, IMI_20151214_071053	3.4E+02	1.2E+03	1.4E+03	17%

The contribution of the rotational component internal forces from the seismic response with respect to the results obtained only from translational component was calculated. The bending moments in two critical sections are presented in Table 1. Additionally bending moments using EC8 part 6 ("EN 1998-6:2005," 2005) response spectrum method is shown too (Zembaty, 2009b). It can be seen that for this set of seismic 6-dof records, respective bending moments at the base from rotational component can be underestimated using the EC8 part 6 formula.

5. EXAMPLE 2: TALL BUILDING

As a second example, a 30-story tall building was analyzed. The building is a reinforced concrete shear wall structure with total height equal to 114 m (see Figure 7). For a similar building design seismic fragility curves have been calculated for South-European Mediterranean zone (Pejovic and Jankovic, 2016). The first 5 natural periods of the building are given in Table 2.

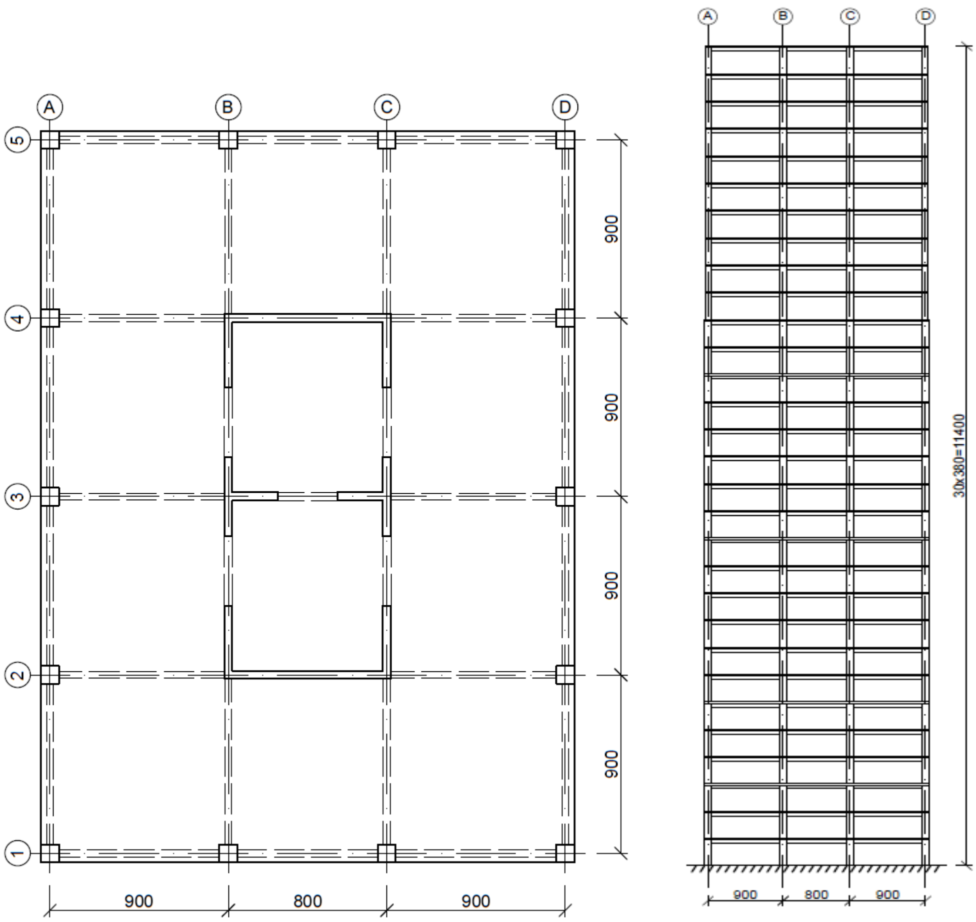

Figure 7. Sketch of the analyzed building.

Table 2. Modal periods [s]

Mode	X	Y	Rotations about Z axis
1	3.40	3.17	2.88
2	0.85	0.99	0.87
3	0.38	0.52	0.44
4	0.22	0.33	0.27
5	0.15	0.23	0.19

The time-history response analyses were carried out using the same simultaneous horizontal and rocking excitations as in the previous example. The results are shown in Figure 8 in which envelop of story shears and overturning moments calculated using eq. (1) are given.
It can be seen again that the contribution of rotational effects is significant. The increase of base shear due to contribution of rotational excitations equals approximately 26% while respective base overturning moment is increased by about 63%.

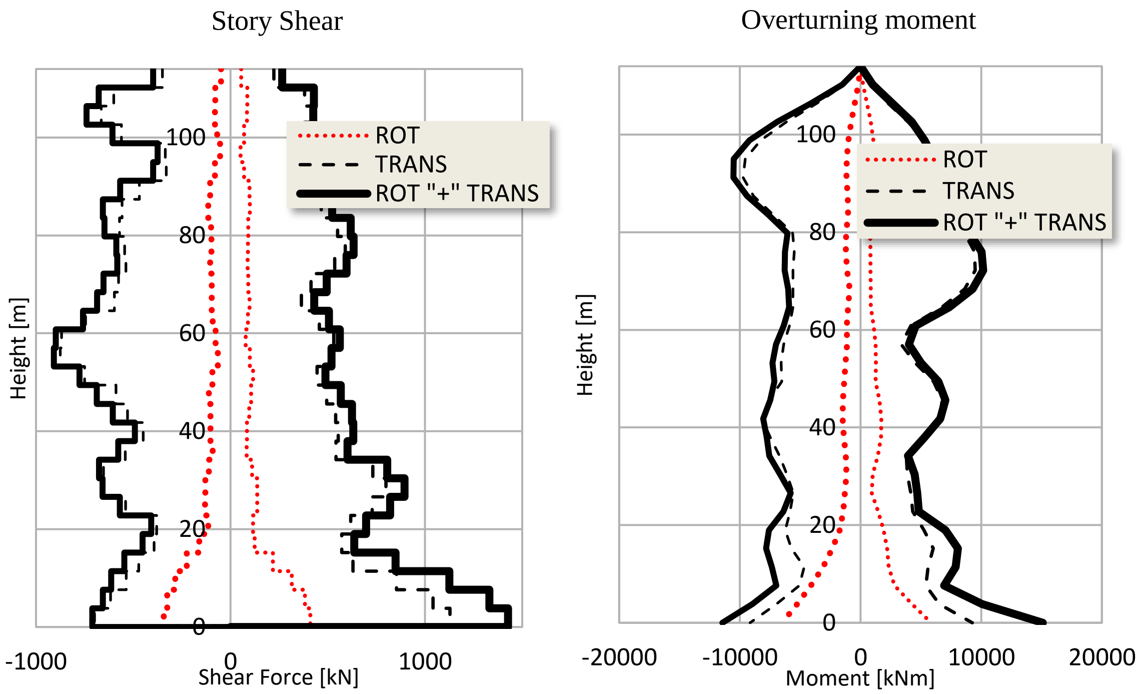

Figure 8. Charts showing envelopes of story shears and overturning moments along the height of the building

6. CONCLUSIONS

While currently neglected in engineering practice, the rotational components of seismic ground motion can significantly contribute to structural response. Presented analyses, which used 6-dof record of moderately intensive seismic tremor, have demonstrated that the inclusion of seismic rotations in computations can result in the increase of internal forces over 60% compared to the analyses using translational component only. This effect can be seen for both of the analysed structures: the 160 m r/c chimney and the 30-story tall building.
This paper has also shown that rotational response spectra of Eurocode 8 part 6 require calibrations. Collecting more and more intensive 6-dof seismic records is crucial to properly calibrate the Eurocode

8 part 6. It should be considered to include rotational spectra in the general Eurocode 8 part 1. However, only when such records are available more accurate rotational response spectra for tall building design can be developed.
It should also be noted that future development of the design loads for tall buildings and slender towers should include also soil-foundation interaction effects which may play important role for more compliant soils.

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