Displacements Caused by Earthquake Motions Detected in Nuclear Power Plants

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ABSTRACT

The paper informs about seismic behaviour of the structural systems inside of main reactor building of WWER Type Slovak NPPs. The information concerns observed displacement motions due to the earthquakes obtained by instrumentation that serves for the control of reactor vessel position. The nuclear reactor shaft tilt measuring sensitive systems, that utilise the hydro-levelling and pendametric methods, have registered motions excited by different far large earthquakes. The paper presents the records illustrating the effects of earthquakes: Sumatra, 26th December 2004; Pakistan, 8th October 2005 and Mozambique, 22nd February 2006. The boundary conditions and effects of soil-structure interaction are discussed in relation to the registered data. The movements detected on the reactor shaft suggest the option of assessment and evaluation of seismic motions in view of direct displacement records rather than those obtained by acceleration and/or velocity sensors. This approach gives additional data that could be utilised like the proof that the temporary tilt of reactor shaft during the earthquake has not exceeded the limit value. It provides also information whether seismic displacement at a site has exhibited residual quasi-static component.

INTRODUCTION

The different monitoring systems are continuously running in every NPP. They support the control and safety of respective NPP during its operation. One from such systems is devoted to monitoring of the angle of the pressure vessel with respect to the reinforced concrete reactor shaft as required by technical directives. The tilt of reactor main jointing plane is usually measured once a year during reactor shut-down. The used 'precise levelling' method follows position of 24 points spaced with 15° angle around the perimeter of the pressure vessel flange. Measuring precision is 0.05 mm. Besides this classical method two independent methods were incorporated to the authorised methods. These are hydro-levelling and pendametric methods. These methods are advantageous as they allow practically continuous measurement of tilt vector even during reactor operation. Such systems are nowadays operating in both Slovak NPPs Jaslovské Bohunice and Mochovce (Ondriš et al.[15]). The measurement of the angle of the pressure vessel considers the slow quasi-static process, therefore the used time step of recording was chosen by value of 5 minutes.

In addition to the basic purpose of these measuring systems, it has been observed their capability to record time histories in very low frequency domain caused by earthquake events. Then, the challenging task is in the analysis of such data and their potential use both for safety control of NPP and for general objectives of earthquake engineering and seismology.

NOTES TO THE STRUCTURE RESPONSE

When the structure is founded on soil deposits or soft media, the resulting motion at the base of the structure will differ from that at the same elevation in the free field due to the soil deformability. For some structures the rocking compliance of the soil is important and may significantly increase the second order effects. Generally, the modelling methods of soil-structure interaction consider: 1) the extent of embedment, 2) the depth of the possible bedrock, 3) the layering of the soil strata, 4) the intrinsic variability of the soil moduli in any single stratum, and 5) the strain dependence of soil properties (shear modulus and damping). The assumption of horizontal layering is generally acceptable. If the finite elements modelling method for soil media is used, the criteria for determining the location of the bottom boundary and the side boundary should be justified. In general, the forcing functions to simulate the earthquake motion are applied at these boundaries. In such cases, it is required to generate an excitation system acting at boundaries such that the response motion of the soil media at the surface free field is identical to the design ground motion. The procedures and theories for generation of such excitation system are the subject of assessment and decision. If the halfspace (lumped parameters) modelling method is used, the parameters used in the analysis for the soil deformability should account for the layering. Besides of that, it should consider the intrinsic variability of soil moduli, and strain dependent properties (Gupta and Trifunac[5], Juhásová et al.[7],[8],[9]).

Mentioned statements concern the strong ground motions at a site rather than the week to medium seismic motions expected in Central Europe, including Slovakia territory. Therefore, supporting calculations refer to linear response and registered tilt motions call for assumption of the consequences of large tectonic blocks movements (translate and rotation) than those apparently attributed to different seismic waves propagation.

Layered subsoil of NPP Jaslovské Bohunice EBO-V2 is represented by loamy loess (thickness 15m = 8.6m + 6.4m and shear wave velocity v_s=200-300 m/s) and the gravel layer below (thickness 20.6m and v_s=700 m/s), Kováč et al.[10]. The bottom of the foundation of the main reactor building is in the depth 8.6 m below the soil surface. The subsoil participates in the seismic response of the structure and secondary of that of the equipment. The assessment of the significant natural frequency of a structure is about 3.1 Hz, measured values were about 3 Hz, calculated values were even smaller, see Table 1. The resulting rotation seismic response can be considered as the combination of seismic input and the response of the structure based on ductile subsoil.

The subsoil of NPP Mochovce EMO is hard rock – andesite (considered v_s=1000 m/s). The assessment of the basic natural frequency of structure vibration is about 3.5 Hz. The resulting rotation seismic response can be considered as the combination of seismic input and the response of the structure based on stiff subsoil.

Table 1. Natural Fequencies of Reactor Building of WWER 440 Type NPP

Calculation method	Boundary conditions	Natural frequencies (Hz)
FEM - modal analysis I (David[4])	stiff	3.16, 5.10, 6.58, 7.51, 18.58
	springs for v_S = 300 m/s	2.23, 2.52, 5.14
	springs for v_S = 200 m/s	1.85, 1.96, 3.60
FEM - modal analysis II (Králik and Šimonovič[11])	springs for v_S = 300 m/s	2.46, 2.73, 3.47, 4.53, 5.56, 14.96
	springs for v_S = 200 m/s	1.96, 3.47, 3.87, 4.20, 14.31, 24.55
Experiment Dukovany (Čejka[2])		3.1, 8.4, 10.3
Experiment Paks (Zola and Da Rin[17])		2.03, 3.14, 6.56, 7.75, 8.63, 9.79

Following available information from measurements and computations and taking into account the thick reinforced concrete foundation, walls and slabs of the main reactor building, the nearly stiff body motion plays predominant role in its seismic response (Campbell et al.[1], Juhásová[7]).

RESPONSE ANALYSIS BASED ON VELOCITY RECORDS

Basic characteristics applied in earthquake engineering are acceleration and displacement response spectra, usually calculated from seismic acceleration records. Having accelerogram $\ddot{x}(t)$, the equation of SDOF system response motion is

$$m\,\ddot{u}(t) + k_D\,\dot{u}(t) + K\,u(t) = -m\,\ddot{x}(t) \tag{1}$$

In the case of known velocity $\dot{x}(t)$ and displacement $x(t)$ time histories, the equation of SDOF system response motion has the form:

$$m\,\ddot{\xi}(t) + k_D\,\dot{\xi}(t) + K\,\xi(t) = K\,x(t) + k_D\,\dot{x}(t) \tag{2}$$

When system has low or very low damping, and $k_D \doteq 0,$ then Eq. (1) may be replaced by

$$m\,\ddot{\xi}(t) + k_D\,\dot{\xi}(t) + K\,\xi(t) \doteq K\,x(t) \tag{3}$$

There is used usual denotation and assumption of viscous damping:

$$\omega_1^2 = \frac{K}{m}, \quad \varepsilon_1 = \zeta\omega_1, \quad k_D = 2\zeta m\omega_1, \quad \omega_1{}' = \omega_1\sqrt{1-\zeta^2} \tag{4}$$

Solution of Eq. (1) at initial displacement $u(0)$ and initial velocity $\dot{u}(0)$ has general form for relative displacement $u(t)$:

$$\begin{aligned} u(t,\omega_1,\zeta) &= e^{-\varepsilon_1 t}\left(u(0)\cos\omega_1' t + \frac{1}{\omega_1'}(\varepsilon_1 u(0) + \dot{u}(0))\sin\omega_1' t\right) - \\ &- \frac{1}{\omega_1'}\int_0^t \ddot{x}(\tau)\mathrm{e}^{-\varepsilon_1(t-\tau)}\sin\omega_1'(t-\tau)\,\mathrm{d}\tau \end{aligned} \tag{5}$$

for relative velocity $\dot{u}(t)$:

$$\dot{u}(t,\omega_1,\zeta) = \mathrm{e}^{-\varepsilon_1 t}\left(\frac{\sin\omega_1^{'} t}{\omega_1^{'}}(-\omega_1^2 u(0) - \varepsilon_1\dot{u}(0)) + \dot{u}(0)\cos\omega_1^{'} t\right) +$$
$$+\frac{\varepsilon_1}{\omega_1^{'}}\int_0^t \ddot{x}(\tau)\mathrm{e}^{-\varepsilon_1(t-\tau)}\sin\omega_1^{'}(t-\tau)\mathrm{d}\tau - \int_0^t \ddot{x}(\tau)\mathrm{e}^{-\varepsilon_1(t-\tau)}\cos\omega_1^{'}(t-\tau)\mathrm{d}\tau \tag{6}$$

and for absolute acceleration $\ddot{\xi}(t)$:

$$\ddot{\xi}(t,\,\omega_1,\,\zeta) = -\omega_1^2 u(t,\,\omega_1,\,\zeta) - 2\varepsilon_1\dot{u}(t,\,\omega_1,\,\zeta) \tag{7}$$

Starting from Eq. (2), the solution has the form:

$$\xi(t,\omega_1,\zeta) = u(t,\omega_1,\zeta) + x(t) = \mathrm{e}^{-\varepsilon_1 t}\left(\xi(0)\cos\omega_1^{'} t + \frac{1}{\omega_1^{'}}\left(\varepsilon_1\xi(0) + \dot{\xi}(0)\right)\sin\omega_1^{'} t\right) +$$
$$+\frac{1}{\omega_1^{'}}\int_0^t(\omega_1^2 x(\tau) + 2\varepsilon_1\dot{x}(\tau))\mathrm{e}^{-\varepsilon_1(t-\tau)}\sin\omega_1^{'}(t-\tau)\mathrm{d}\tau \tag{8}$$

$$\dot{\xi}(t,\omega_1,\zeta) = \dot{u}(t,\omega_1,\zeta) + \dot{x}(t) = \mathrm{e}^{-\varepsilon_1 t}\left(\frac{\sin\,\omega_1^{'}t}{\omega_1^{'}}(-\omega_1^2\xi(0) - \varepsilon_1\dot{\xi}(0)) + \dot{\xi}(0)\cos\,\omega_1^{'}t\right) -$$
$$-\frac{\varepsilon_1}{\omega_1^{'}}\int_0^t(\omega_1^2 x(\tau) + 2\varepsilon_1\dot{x}(\tau))\mathrm{e}^{-\varepsilon_1(t-\tau)}\sin\,\omega_1^{'}(t-\tau)\mathrm{d}\tau + \int_0^t(\omega_1^2 x(\tau) + 2\varepsilon_1\dot{x}(\tau))\times \tag{9}$$
$$\times\,\mathrm{e}^{-\varepsilon_1(t-\tau)}\cos\,\omega_1^{'}(t-\tau)\mathrm{d}\tau$$

and for $\ddot{\xi}(t,\,\omega_1,\,\zeta)$ Eq. (7) is valid.

This approach utilises the knowledge of both velocity and displacement time histories of ground motion. The velocity is recorded directly and displacement is obtained by integration of velocity time history including necessary filtering of spurious motions. The procedure is convenient for use in countries with moderate seismicity, where majority of seismic stations is using velocity sensors. Monitoring systems and automation of data acquisition allow further detailed analysis of obtained data[6], [12]. The velocity record in vertical direction obtained at Slovak seismic station Červenica is shown in Fig. 1. The sampling frequency was 100 Hz. Lower frequencies observed in this record suggest their values about f =0.080 Hz (or T = 12.41 s), but also about f = 0.029 Hz (or T = 34.48 s).

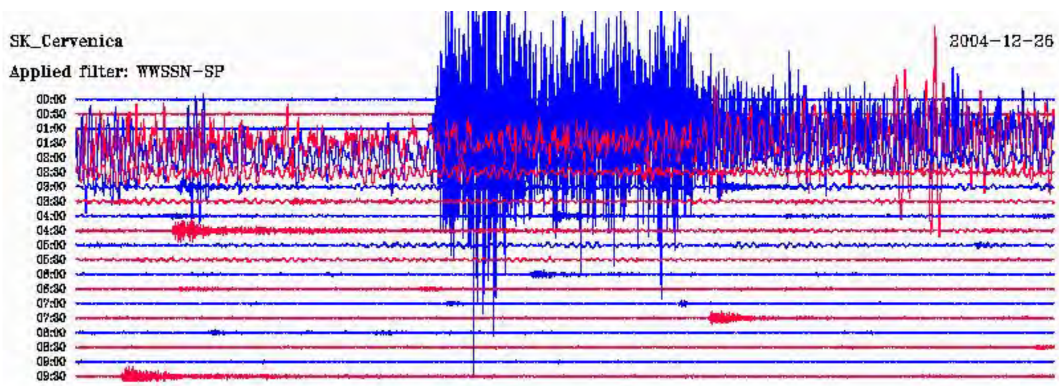

Fig. 1 Earthquake 26 Dec 2004, Vertical Velocity Record from Seismic Station Červenica - CRVS

MEASURING METHODS AND SYSTEMS USED FOR TILT CONTROL

Tilt measuring systems running in the Slovak EBO, EMO power plants use methods of hydro-levelling and pendametry with unified optoelectronic measuring of hydrostatic liquid level and damped pendulum wire position, respectively. In contrast with classical levelling method, which allows measurement of this quantity only during the reactor shut-down state (which is not the operational state), the used measuring principles and applied methods allow a practically continuous measuring of reactor tilt vector. The amplitude of tilt vector in this paper is defined as maximum height difference of two points in the reactor flange plane on the flange diameter basis (Fig. 2a). The angle of tilt vector is given by angle orientation of line with maximum tilt lying in flange plane to the reactor coordinate system. A schematic diagram of the reactor tilt measuring system is shown in Fig. 2b.

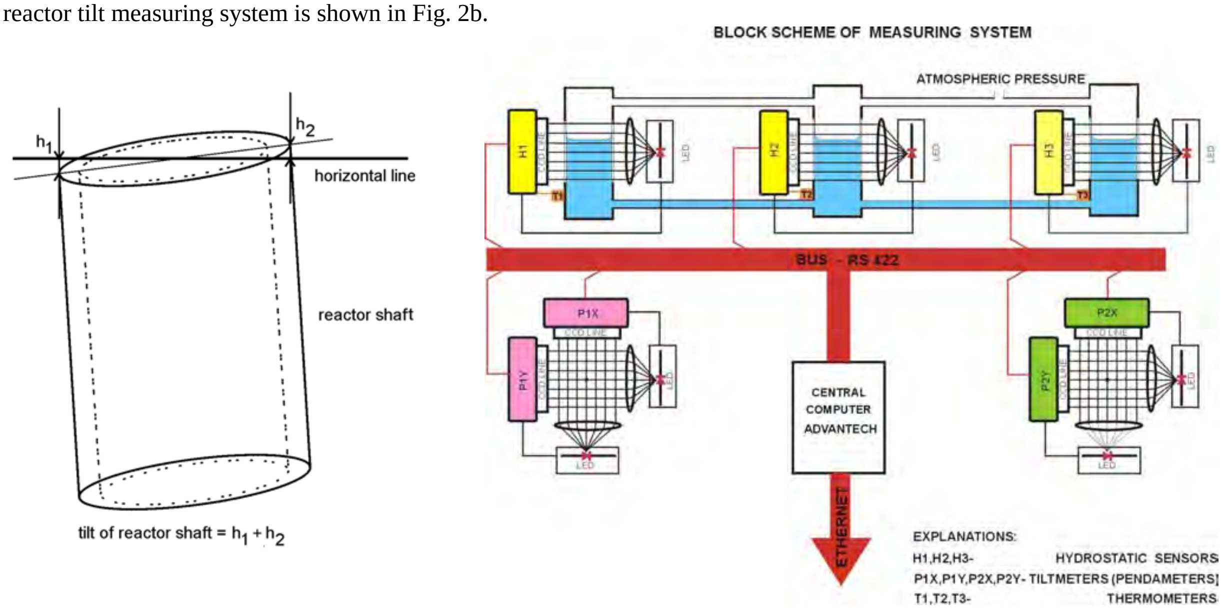

Fig. 2 a) Scheme of Reference Amplitude of Tilt Vector Related to the Flange Diameter – Left; b) Block Scheme of Measuring Hydro-Levelling and Pendametric System - Right

Hydro-levelling is a well known levelling method, and in connection with the application of optoelectronics and information technology has some advantages to purely optical methods. Minimum three hydro-levelling sensors are necessary in order to measure reactor shaft tilt vector. Three hydro-levelling sensors (H_{1-3}) that were developed and made in the Institute of Measurement Science, Slovak Academy of Sciences are used for reactor tilt vector measurement (Ondriš et al. [13], [14], [15]). The optoelectronic sensor in system of connected vessels consists of a flat window cell made of a metal frame with optical glass and an optoelectronic system for hydrostatic liquid level height measurement. This optoelectronic part is based on a CCD line image sensor. Hydraulic and pneumatic pipes secure the interconnection of sensors. This system of connected vessels is also interconnected with power supply and via communication cables with the central industrial computer. Liquid temperature in sensors is measured by means of thermometers built in the sensors. This temperature is used for the correction of measured data that are influenced by liquid temperature dilatation. The liquid levels in individual vessels lie in one horizontal plane when certain physical conditions are fulfilled. This plane can then serve as the reference plane for the elevations differences measured between individual points. The range of height difference measurement is ±10 mm, the precision is 0.01 mm. The view of hydro-levelling sensor is in Fig. 3a.

The pendametric method uses the properties of a vertically damped pendulum. Electromagnetic damping secures sufficiently high damping ratio as critical one. It does not allow the jump crossing of pendulum vertical position after its return. The pendulum hinging point is connected to the measured object. The position of the pendulum wire is measured bi-axially in a reference plane that is usually horizontal. The wire's position in the reference plane and its length determine the reactor shaft tilt. The optoelectronic method is used for this position measurement similarly as in the hydro-levelling method. Such measurement unification simplifies the whole measuring system.

Although one biaxial pendametric sensor (Fig. 3b) is sufficient for tilt vector measurement, the measuring system incorporates two pendametric sensors (P_{1-2}) as a purpose-built redundancy. Interconnection by power supply and standard RS 422 communication cables are also common for hydro-levelling sensors. The measuring range of the pendameter wire position is ±2 mm in both coordinate axes; the resolution is 0.001 mm. The length of the pendulum wire is 2 m.

The topology of the three hydro-levelling sensors located on the reactor shaft perimeter allows measurement of its tilt vector in the power plant coordinate system. All sensors are fixed in the reinforced concrete reactor shaft body with special rods preventing any damage and not disturbing the reactor hermetic zone.

Central personal computer allows for a user-friendly computation, presentation, and archiving/storage of measured data of the reactor shaft tilt. The measurement regime, including the measuring (sampling) interval, may be programmed according to the user requirements. Data obtained from measurements are recalculated to the values of reference tilt amplitude vector and values of its angle in local NPP coordinate system.

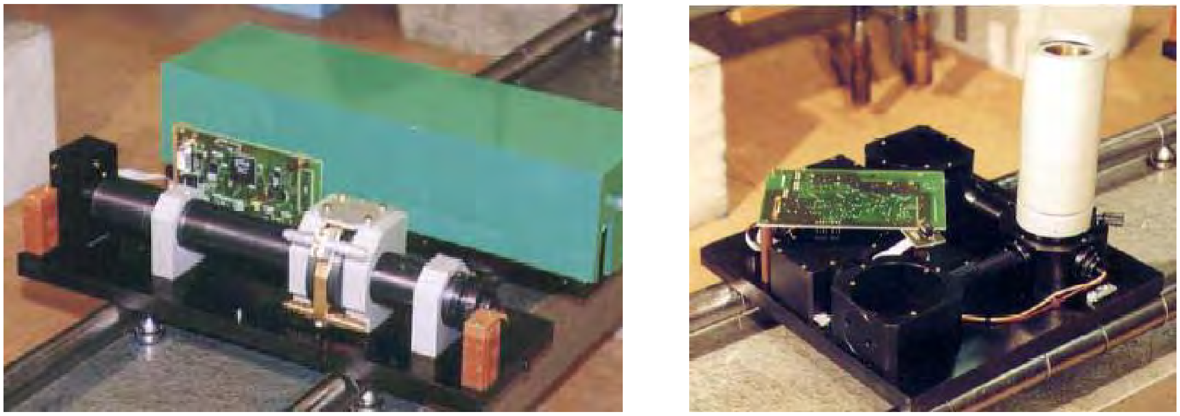

Fig. 3 a) Hydro-Levelling Sensor – Left; b) Pendametric Sensor - Right

OBSERVATIONS DUE TO EARTHQUAKE EFFECTS

Permanent recording and evaluation of obtained records brought information that low quasistatic movements of the reactor shaft correspond prevailingly to operational effects and subsoil conditions. However, there appeared also tilt motions caused by far strong earthquakes. Therefore, the attention was devoted to such records in light of knowledge from few latests large earthquakes.

Firstly are presented the records obtained from tilt measurement due to Sumatra 2004 large earthquake[16]. These records show the time dependences of the reactor tilt vector reference amplitudes given in relative units (mm per flange diameter) as is shown in Fig. 2a. The signals recorded by the tilt measuring systems in NPP EBO-V2 are depicted in Figure 4. There were two perturbations: the first one started on 23rd December 2004 at 15.40 UTC caused by the earthquake between Australia and Antarctica and the second one started on 26th December 2004 at 01.20 UTC caused by the earthquake off the Indonesian coast with magnitude 9.3. Original seismic event had started at 00:58:50 UTC with coordinates LAT 3.5N, LONG 95.72^{E} and depth 10 km. Amplitudes detected by pendametric sensors P1, P2 reached higher values, smaller amplitude values were recorded by hydro-levelling sensors. The reason of smaller amplitudes is due to the delay that was caused by the time interval needed for reaching the equilibrium positions of used liquid. The time of this earthquake effect corresponds to regular seismological records obtained by national seismic stations network.

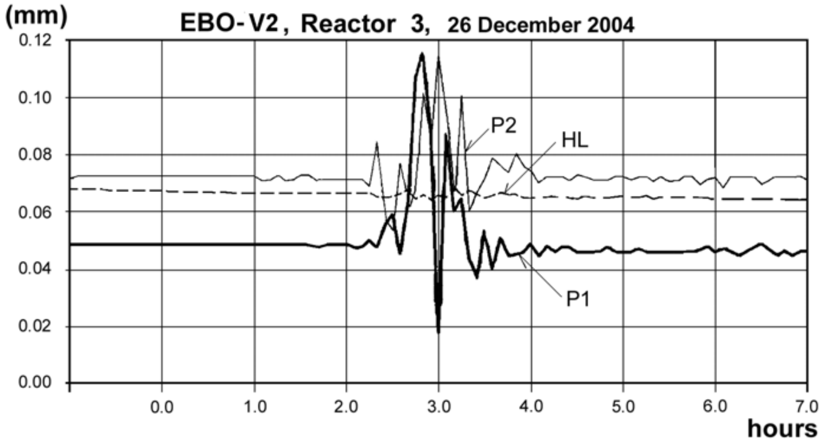

Fig. 4 NPP Jaslovské Bohunice EBO-V2, Reactor 3. Reference Shaft Tilt Amplitude Record, 26th Dec 2004

Next figure refers to NPP Mochovce EMO. The power plant coordinate system and position of tilt measuring sensors are following: South – *x* direction; East – *y* direction; Hydro-levelling sensors are placed on east, west and north sides, pendametric sensor P1 on west side and P2 on north side.

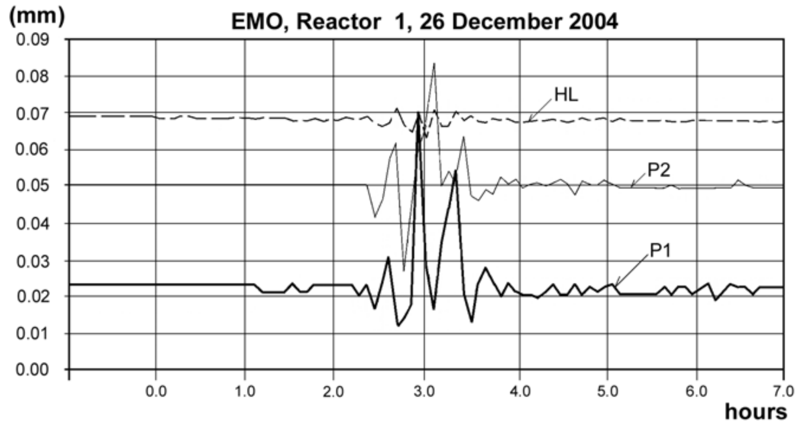

Fig. 5 NPP Mochovce EMO, Reactor 1. Reference Shaft Tilt Amplitude Record, 26th Dec 2004

It can be seen from Figs. 4, 5 that the motion in NPP EMO is slightly different from that one recorded in NPP EBO-V2, both in shapes and amplitudes. The registered double reference amplitudes were:
NPP EBO-V2 P1 – 0.097 mm; P2 – 0.061 mm;
NPP EMO P1 – 0.058 mm; P2 – 0.059 mm.

The further examples present the reference shaft tilt amplitude records due to the earthquake in Pakistan from October, 8th, 2005 and Mozambique one from February, 22nd, 2006. The Pakistan earthquake started at 3:50 UTC, the coordinates were LAT 34.47N, LONG 73.50E, depth 10 km, and magnitude 7.6. Fig. 6 shows its effect on EBO-V2 reference shaft tilt amplitude recorded by pendametric sensor P1 on the shaft of reactor 4. The Mozambique earthquake started at 22:19 UTC, its coordinates were LAT 21.29S, LONG 33.44E, depth 10 km and magnitude 7.6. Fig. 7 presents its effect on EBO-V2 reference shaft tilt amplitude recorded by pendametric sensor P1 on the shaft of reactor 3.

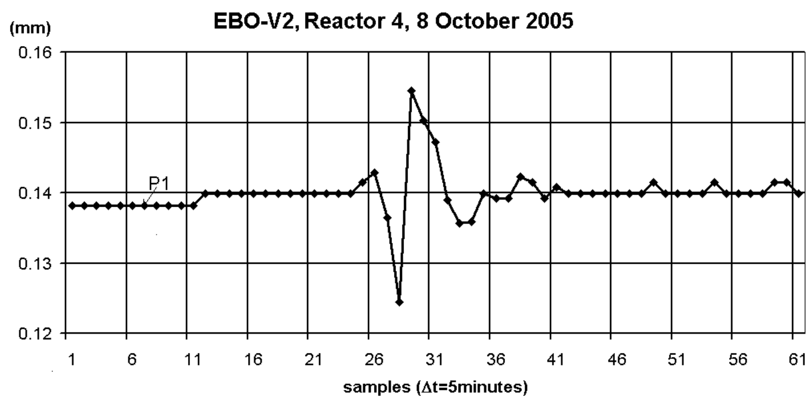

Fig. 6 NPP Jaslovské Bohunice EBO-V2, Reactor 4. Reference Shaft Tilt Amplitude Record Due to Pakistan Earthquake from 8th Oct 2005 (No Record from the Shaft of Reactor 3)

Either these values are low and far away from those that could call for any action or intervention, this information can be generally utilised. The obtained data can be converted into radians – and considered as a part of rotation seismic motions as is shown in Tables 2 and 3.

However, time histories of the registered tilt vectors and their shapes are influenced by the sampling time step that was about 5 minutes. Actually, the measuring system was designed and serves for quasi-static tilt measurement. Therefore, the obtained data suggest that there exist the intermediate values of these slow motions which can be smaller or higher than the registered values. Philosophy of these continuous tilt measurements is based on incremental values related to the geodetic measurements executed during the last shut-down of the respective NPP unit.

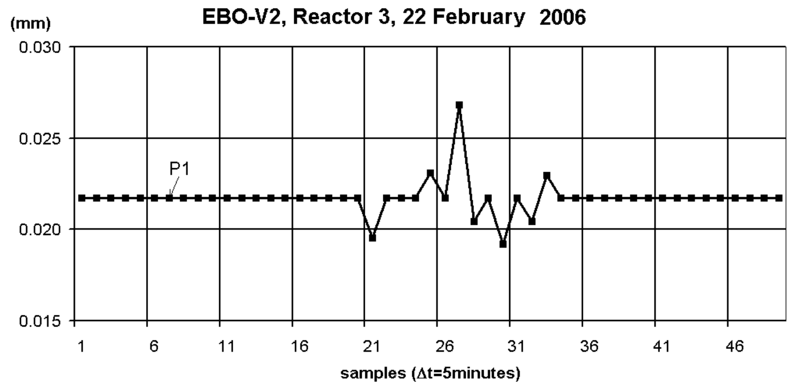

Fig. 7 NPP Jaslovské Bohunice EBO-V2, Reactor 3. Reference Shaft Tilt Amplitude Record Due to Mozambique Earthquake from 22nd Feb 2006

Table 2. Maximum and Minimum Reference Tilt Vector (mm) Related to Data from NPPs Reactor Shaft Tilt Measurements – Pendametric P1 and P2 Sensors

Description of a site	Min tilt (mm)	Max tilt (mm)	Min seismic amplitude (mm)	Max seismic amplitude (mm)	Max seismic double ampl. (mm)
EBO-V2, Reactor 3 - P1, 26 Dec 2004	0.0166	0.1155	0.0488	0.0500	0.0988
EBO-V2, Reactor 3 - P2, 26 Dec 2004	0.0537	0.1139	0.0171	0.0431	0.0602
EMO, Reactor 1 - P1, 26 Dec 2004	0.0123	0.0715	0.0108	0.0485	0.0592
EMO, Reactor 1 - P2, 26 Dec 2004	0.0277	0.0846	0.0223	0.0346	0.0569
EBO-V2, Reactor 4 - P1, 8 Oct 2005	0.1240	0.1540	0.0133	0.0167	0.0300
EBO-V2, Reactor 3 - P1, 22 Feb 2006	0.0192	0.0269	0.0025	0.0053	0.0078

Table 3. Maximum and Minimum Rotations (radians) in View of Tilt Motions Related to Data from NPPs Reactor Shaft Tilt Measurements – Pendametric P1 and P2 Sensors

Description of a site	Min rotation (rad)	Maximum rotation (rad)	Min seismic rot. amplitude (rad)	Max seismic rot. amplitude (rad)	Max seismic rot. double ampl (rad)
EBO-V2 Reactor 3 - P1,26,Dec.,2004	4.6236e-6	3.2073e-5	1.3549e-5	1.3901e-5	2.7449e-5
EBO-V2 Reactor 3 - P2,26,Dec.,2004	1.4911e-5	3.1627e-5	4.7569e-6	1.1959e-5	1.6716e-5
EMO Reactor 1 - P1,26 Dec 2004	3.2389e-6	1.8826e-5	2.8341e-6	1.2753e-5	1.5587e-5
EMO Reactor 1 - P2,26 Dec 2004	7.6923e-6	2.2267e-5	5.8705e-6	9.1093e-6	1.4980e-5
EBO-V2 Reactor 4 - P1,8 Oct 2005	3.4444e-5	4.2778e-5	3.7037e-6	4.6296e-6	8.3333e-6
EBO-V2 Reactor 3 - P1,22 Feb 2006	5.3241e-6	7.4846e-6	6.9444e-7	1.4660e-6	2.1604e-6

In terms of safe operation of the power plant, it would be feasible and more valuable to have directly measured information about reactor position changes in terms of displacements, than those obtained by doubled integration with filtering of recorded response accelerations, e.g. from the NPP seismic response monitoring system[3]. For the sake of more credible and precise measurement of the reactor body position during the earthquake, the option exists to extend and/or improve the operating reliable measuring system. The solution can follow the prevention of the existing measuring system, with consequent completion with the additional units. In such complementary recording units, firstly the measuring frequency should increase app. up to 10 Hz and then faster pendametric sensors would support higher sampling frequency or smaller sampling time step. The full synchronisation of local power plant time with UTC is to be completed.

CONCLUSIONS

The structures built on stiff subsoil (hard rock) and on the soft one present different response to the actions of far or near source earthquakes. Any information available from monitoring systems can contribute to the knowledge about motions of NPP structures or, in general, about seismic effects at a site. Uncertainties connected with very low frequency components in acceleration (or velocity) records can be limited when displacement/rotation supporting records are available. Records of such static-dynamic displacements based on measured data of reactor shaft tilt can be utilised in two directions: firstly giving the proof that the temporary tilt of shaft during any earthquake has not exceeded the limit value; secondly providing information whether seismic displacement or seismic rotation at a site has exhibited a residual quasi-static component. To this end, the prepared special set of instrumentation could cover the frequency range that content is usually unknown and therefore is disregarded.

ACKNOWLEDGEMENTS

The research was partially founded by projects VEGA 2/4078/24 and 2/7114/27. The financial support is gratefully acknowledged.

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