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BUILDING TILT CONTROL BY BASE CONTROL SYSTEM (BCS)

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ABSTRACT

At present, more and more nuclear power plants (NPPs) are under construction in the areas of high seismicity with a peak ground acceleration (PGA) from 0.5 to 1.0g. It is not always possible to find the sites with a solid bedrock base to place a NPP unit in these cases, as well as to provide the necessary seismic capacity. It is also known that a big number of existing NPPs' structures, including Reactor Building (RB) and reactor island structures are located on relatively soft soils or on soils with uneven stiffness, subjected to uneven soil compaction and subsidence, and, as a consequence, progressive tilt of the entire structure. It causes a particularly significant problem for RB structures, which have a very strict limit on a vertical axis orientation, influencing control rod drives (CRD) performance that is one of the major safety related systems of NPP.

The application of a modern three dimensional (3D) seismic isolation system for NPP buildings and structures, based on using coil spring isolators and 3D viscodampers known as the Base Control System (BCS), allows completely and cost-effectively solve the problem of NPP's seismic capacity.

In addition, BCS provides the possibility of a building orientation control during the entire life-service and can easily and reliably compensate all uneven soil subsidence that could happen during a NPP's long-term operation.

INTRODUCTION

Long-term field observations showed that the spatial position of the RB and reactor vessel in some NPP sites have a progressive tilt caused by uneven soil settlement (see Figure 1) [1]. RB tilt for the reactor of WWER-1000 MW type is limited by the slope of a reactor's main flange and is 1.0 mm/m (0.001 rad) as the maximum allowable [2].

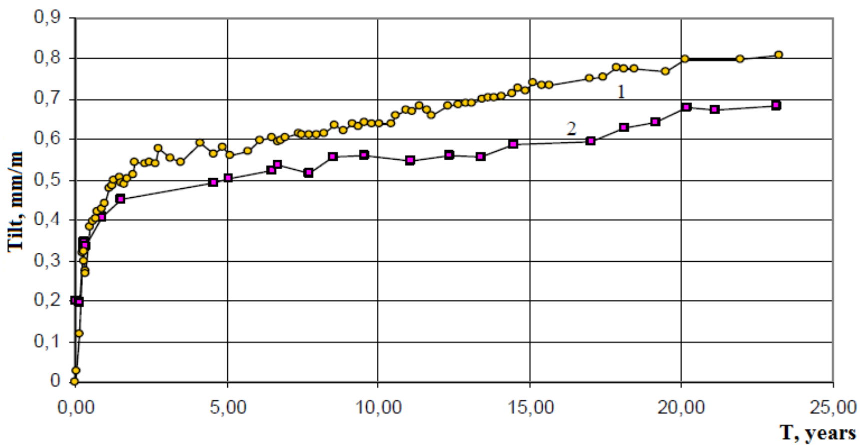

Figure 1 Results of observations of a RB tilt (1) and a reactor vessel tilt (2)

The paper deals with a typical 1000/1200 MWt NPP's RB equipped with the BCS seismic isolation system having a tilt due to uneven soil settlement or eccentricity of the centre of mass of the building (or a combination of both cases).

It is shown that the RB tilt correction might be performed by the installation of additional shims in the BCS spring isolators according to the conventional and proven procedure.

TILT MODELLING

Evaluation of a tilt value for a building on a regular BSC system

If the Reactor Building (RB) is installed on a grid with a regular arrangement of springs isolators and the RB's centre of mass is projected into the point that does not coincide with the centre of the spring system, the building receives a tilt. Below we estimate the tilt value under the following assumptions and input data (see Figure 2):

- spring blocks in regular square grid nodes with ***L/N*** increments, where ***N*** is the number of rows in both horizontal directions;
- building mass ***m;***
- RB center of mass $\underline{R}_C = x_C \underline{i} + y_C \underline{j} + z_C \underline{k}$ (coordinate origin is in point ***O*** on the plane overlying the springs);
- the stiffness of each spring unit is ***c***;
- upper and lower foundation slabs are rigid.

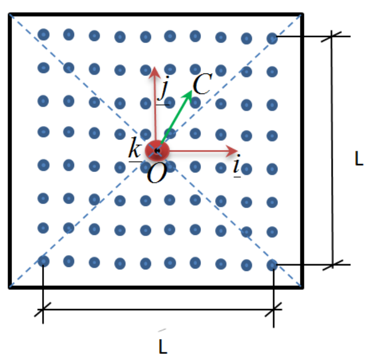

Figure 2. Layout of BSC system. Top view.

The balance equation of forces:

$$-mg\underline{k} - \sum_i \sum_j c\Delta z_{ij}\underline{k} = 0 \tag{1}$$

$\Delta z_{ij} \equiv z_{ij} - l_0$, z_{ij} – springs height after deformation, l_0 – initial undeformed height, i, j – numbers of rows in horizontal directions.

The balance equation of moments relative to point ***O***:

$$-\underline{R}_C \times \underline{k}mg - \sum_i \sum_j \underline{r}_{ij} \times \underline{k}c\Delta z_{ij} = 0 \tag{2}$$

where $\underline{r}_{ij} = a_{ij}\underline{i} + b_{ij}\underline{j}$ – position of the spring unit ***(i,j)***.

Since the upper and lower foundation slabs are rigid in the model, the upper points of the springs belong to the plane. A constant translation of the plane balances the weight of the building and the tilt of the plane compensates the moment $-\underline{R}_C \times \underline{k}mg$.

The deformations of the springs can be described by the following expression:

$$\Delta z_{ij} = -\frac{mg}{cN^2} + \theta b_{ij} - \varphi a_{ij} \tag{3}$$

Here θ – angle of a *small* rotation of the RB around the axis $\underline{i}$, φ – around the axis $\underline{j}$.

These deformations satisfy the Equation (1), since the displacement terms caused by the rotation give the total of zero.

Substituting (3) into (2), we obtain:

$$\underline{j}x_C mg - \underline{i}y_C mg = c\sum_i\sum_j\left(\underbrace{-\underline{j}a_{ij}b_{ij}\theta}_{=0} + \underline{j}a_{ij}{}^2\varphi + \underline{i}b_{ij}^2\theta - \underbrace{\underline{i}a_{ij}b_{ij}\varphi}_{=0}\right) \tag{4}$$

The sums with products of coordinates $a_{ij}b_{ij}$ are equal to zero, since in the sum all products have pairs equal in absolute value and opposite in a sign.

If ***N*** is odd, then

$$\sum_i\sum_j\left(a_{ij}{}^2\right) = 2Nu^2\sum_{s=1}^{(N-1)/2} s^2 = NL^2\frac{(N+1)}{12} \tag{5}$$

If ***N*** is even, then

$$\sum_i\sum_j\left(a_{ij}{}^2\right) = \frac{1}{2}Nu^2\sum_{s=1}^{N/2}(2s-1)^2 = \frac{N^2L^2}{12}\frac{(N+1)}{(N-1)} \tag{6}$$

here ***u=L/(N-1)*** is the distance between adjacent rows.

Thus we have explicit expressions for tilt angels:

$$\varphi = \frac{x_C mg}{cK(L,N)},\ \theta = -\frac{y_C mg}{cK(L,N)}, \tag{7}$$

where $K(L,N)$ – expressions (5) or (6).

For the given realistic parameters $x_c = 3\ m$, $L = 80\ m$, $m = 258000\ t$, $c = 1.11e8\ N/m$, $N = 24$:

$$\varphi \approx 0.0002 \tag{8}$$

The tilt angle is 20% of the maximum allowable 0.001 *rad* in static [2].

Modelling of the lower foundation slab tilt

Let us assume that the lower foundation slab gave the tilt on a *small* angle $\theta_1\underline{i} + \varphi_1\underline{j}$ due to the uneven soil settlement.

The projection of the balance equation of forces on the vertical axis:

$$-mg - \sum_i\sum_j c\Delta z_{ij} = 0, \tag{9}$$

The balance equation of moments relative to point ***O***:

$$z_C mg\left(\theta_2\underline{i} + \varphi_2\underline{j}\right) - \sum_i\sum_j \underline{r}_{ij} \times \underline{k}c\Delta z_{ij} = 0 \tag{10}$$

where θ_2 – angle of a small rotation of the building around the axis $\underline{i}$, φ_2 – around the axis $\underline{j}$.

By analogy with (3), axial deformations of the springs can be described by the following expression:

$$\Delta z_{ij} = -\frac{mg}{cN^2} + (\theta_2 - \theta_1)b_{ij} - (\varphi_2 - \varphi_1)a_{ij} \tag{11}$$

These deformations satisfy the Equation (9), since the displacement terms caused by the rotation give a total of zero.

Substituting (11) into (10), we obtain:

$$z_C mg\left(\theta_2 \underline{i} + \varphi_2 \underline{j}\right) - c\sum_i \sum_j \left(\underbrace{-\underline{j} a_{ij} b_{ij} (\theta_2 - \theta_1)}_{=0} + \underline{j} a_{ij}^{\ 2} (\varphi_2 - \varphi_1) + \underline{i} b_{ij}^2 (\theta_2 - \theta_1) - \underbrace{\underline{i} a_{ij} b_{ij} (\varphi_2 - \varphi_1)}_{=0} \right) = 0 \quad (12)$$

The Equation (12) gives a relation between angles of the tilt of upper (building) and lower foundation slabs:

$$\theta_2 = \theta_1 \left(1 + \frac{z_C mg}{c \cdot K(L,N) - z_C mg} \right) \quad (13)$$

$$\varphi_2 = \varphi_1 \left(1 + \frac{z_C mg}{c \cdot K(L,N) - z_C mg} \right) \quad (14)$$

When the lower foundation slab is rotated to a certain angle, the building rotates at the angle slightly greater than the angle of rotation of the basement.

Typically $c \cdot K(L,N) >> z_C mg$ so the building rotates together with the lower foundation and there are no issues of stability loss.

For the parameters from the previous section (*x_c = 3 m, L = 80 m, m = 258000 t, c = 1.11e8 N/m, N = 24, z_c=35 m)*, the expression in brackets in (13)-(14) gives 1.002. That is, the building gives almost the same tilt as the lower foundation slab.

TILT COMPENSATION

It is possible to eliminate the tilt of the building by applying the moment in the direction opposite to the tilt. An obvious way to create such a moment is to increase the reaction of springs located on the corresponding side from the axis of the building rotation. Technically this is implemented by installing steel shims with thicknesses $\boldsymbol{t_{ij}}$ on these springs:

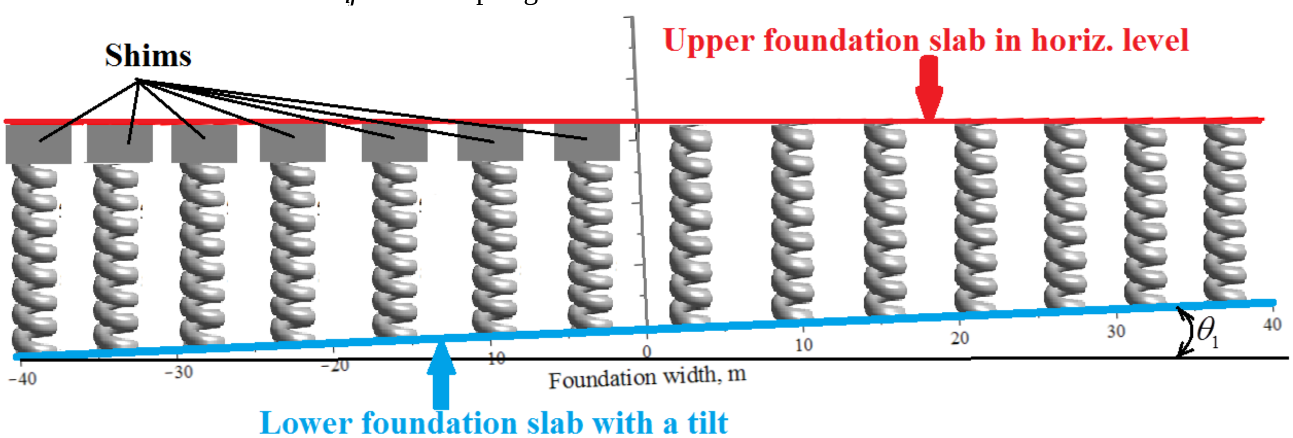

Figure 3. Tilt compensation in one vertical plane

Deformation of springs with shims for the case of no building tilt $\theta_2 = 0$, $\varphi_2 = 0$:

$$\Delta z_{ij} = -\Delta z_* - \theta_1 b_{ij} + \varphi_1 a_{ij} - t \quad (15)$$

Deformation of springs without shims:

$$\Delta z_{ij} = -\Delta z_* - \theta_1 b_{ij} + \varphi_1 a_{ij} \quad (16)$$

where Δz_* – nominal deadload deformation of springs.

Substituting (15), (16) into the equation (10) we obtain:

$$-cK(L,N)\left(\theta_1 \underline{i} + \varphi_1 \underline{j}\right) - \sum_i \sum_j \underline{r}_{ij} \times \underline{k} c t_{ij} = 0 \quad (17)$$

$$c\sum_i \sum_j t_{ij} (\underline{j} a_{ij} - \underline{i} b_{ij}) = cK(L,N)\left(\theta_1 \underline{i} + \varphi_1 \underline{j}\right) \quad (18)$$

In (17)-(19) the summation over ***i,j*** is running for spring blocks with shims. Equation (18) expresses the condition of the tilt compensation by the moment of additional forces in springs with shims.

$$\begin{cases} \sum_i \sum_j t_{ij} b_{ij} = -K(L,N)\theta_1 \\ \sum_i \sum_j t_{ij} a_{ij} = K(L,N)\varphi_1 \end{cases} \quad (19)$$

The determination of the shim thicknesses t_{ij} and the corresponding springs with the position $\underline{r}_{ij} = a_{ij}\underline{i} + b_{ij}\underline{j}$ satisfying (19) is a problem with a lot of solutions. The following solution might be offered as the most obvious one:

1. Initially, the tilt is removed in one direction. Let us assume it is a reverse turn correcting the tilt around the axis $\underline{i}$.
2. The springs for the shims installation must fulfil the condition: the sign of $-\theta_1$ and the sign of the coordinate b_{ij} have to coincide for spring blocks. That is, two of the four quadrants (see Figure 3).
3. Shims t_{ij} are of constant thickness $t_1 = \dfrac{K(L,N)|\theta_1|}{\sum_i \sum_j b_{ij}}$

$$t_1 = \frac{2}{3} L|\theta_1| - \text{ for odd N} \quad (20)$$

$$t_1 = \frac{2}{3}\frac{L(N+1)}{N}|\theta_1| - \text{for even N} \quad (21)$$

4. Since the force field created in this manner is symmetrical to the axis $\underline{j}$, the building does not rotate around $\underline{j}$.
5. Next, the tilt around the axis $\underline{j}$ is corrected. The springs for the shims installation must fulfil the condition: the sign of φ_1 and the sign of the coordinate a_{ij} have to coincide for spring blocks. That is, two of the four quadrants. The thickness of the second set of shims:

$$t_2 = \frac{2}{3} L|\varphi_1| - \text{for odd N} \quad (22)$$

$$t_2 = \frac{2}{3}\frac{L(N+1)}{N}|\varphi_1| - \text{for even N} \quad (23)$$

To compensate the static tilt of 20% of the maximum allowable (see the example above), the thickness of shims should be 11 mm at the nominal static preload of 40 mm.

CONCLUSION

1. If the seismic isolation system has a regular arrangement (spring blocks are along the nodes of the square grid) and the projection of the center of mass of the building does not coincide with the geometric center of the SIS, the building will get a tilt.
2. With the tilt of the lower foundation slab, the building gives almost the same tilt.
3. It is possible to correct the tilts caused by both the tilt of the lower foundation slab and the tilt caused by the eccentricity of the center of mass of the building or a combination of both cases. The algorithm for leveling the building with appropriate shims installation is proposed, thicknesses and locations are determined.

4. Apparently, at the stage of construction of foundation slabs on the regular SIS system, an early compensation of the tilt caused by a known eccentricity is necessary. The compensation caused by uneven soil settlement is possible during the operation of the building.
5. The above approach can be transformed for the case of a rectangular foundation shape.

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