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Contributions on the Seismic Calculation of Grain Steel Silos by Considering the Seismic Action as an Effect

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Abstract – **Both at the national and international level, the specialized literature devotes many lines to the description of the various seismic calculation methods largely applicable to buildings. Very few of these descriptions and references, however, are applicable to earthquake analysis for the verification of steel or reinforced concrete silos. The most advanced international seismic design standard EN 1998, presents through its fourth part, principles of anti-seismic design of silos, emphasizing two approaches: the approach in which the earthquake can be considered action and the approach in which the earthquake can be considered in the calculation as an effect. The article contributes with an alternative seismic calculation by effects in which the calculation principles of SR EN 1998-4 will be followed.**

Keywords – earthquake, Eurocode 8, seismic analysis, silo design

1. INTRODUCTION. TERMS DESCRIPTION: ACTION AND EFFECT

Many authors have issued different theories and analytical interpretations all with the aim of finding the best way to determine the behavior of structures under the action of earthquakes. Many pages, both in the international and national specialized literature, have been dedicated to the calculation concepts of seismic ACTION, but very few dealing with the concept of seismic calculation through the direct evaluation of EFFECTS. The EFFECTS approach is not established in the field of designing structures for buildings, it being mainly used for the design of special constructions such as silos and tanks.

To help better understand the concept of anti-seismic design based solely on effects assessment, I propose to define the key terms: "ACTION" and "EFFECT". A reference in this regard is the SR EN 1990 design code, which assigns the following definitions to these two terms:

"ACTION" (F) – set of forces (loads) applied to the structure (direct action); set of imposed deformations or accelerations caused by, for example, changes in temperature, variation in humidity, differential settlement or earthquakes.

Seismic design concepts require the definition of the associated notion of "SEISMIC ACTION" (AE). Therefore, "SEISMIC ACTION" (AE) is defined as the action that occurs due to the movement of the ground during an earthquake.

"ACTION EFFECT"(E) – effect of actions on structural elements (eg internal force, moment, stress, deformation) or on the whole structure (eg displacement, rotation).

In a preliminary estimate, we can state that an approach to seismic evaluation through ACTION will prove, in most situations, favorable because through it the principles and theoretical foundations of SR EN 1990 can be best applied, leading in final to accurate equation writing for seismic design situations. The EFFECTS approach to seismic assessment is a conservative alternative, which will involve converting the combination equation for seismic design situations into an equation for the ultimate resistance limit state by eliminating the mathematical formulation based on the seismic spectrum. Consequently, the focus will be on the direct determination of the dynamic pressures, as a response of the stored material, and how to combine them with the rest of the permanent and variable actions imposed by the design assumptions.

Although the seismic evaluation approach through EFFECTS is presented by Eurocode as a simplified method, in practice, its application often leads to structural responses containing gross errors. As shown in engineering practice, most of the errors come from the way the design equations are written.

2. SEISMIC DESIGN EQUATION CONCEPTS FOR BUILDINGS [SR EN 1990, SR EN 1998 AND P100/1-2013]

As is already known, the design code that regulates the anti-earthquake design of buildings is Eurocode 8. In Romania, the general seismic design prescriptions were taken from the European standard through the SR EN 1998 series of norms, the National Determined Parameters (NDP's) being presented and detailed in Normative P100/1-2013.

It is necessary, right from the beginning, to know the scope of these regulations, an aspect imposed by the complexity of the seismic action assessment.

Eurocode 8, through its principles and application rules, presents technical design prescriptions for a wide range of constructions, from buildings to special constructions such as dams, dams, reservoirs, silos, towers, bridges, etc.

Extract from the presentation of the structure by parts of SR EN 1998 will be considered relevant in the paper: Part 1 - considered fundamental since it contains all the basic concepts, the definition of seismic action, the rules for buildings and Part 4 - relevant for establishing the analytical calculation model of the silos.

Different from many presentations made on this topic, the presentation of the seismic assessment approach through ACTION will be made starting from the design equation in the special assumption extracted from Section 6 of SR EN 1990, relations (6.12a) and (6.12b):

$$E_d = E\{G_{k,j}; P; A_{Ed}; \psi_{2,i}Q_{k,j}\} j \geq 1; i \geq 1 \tag{1}$$

$$\sum_{j\geq 1} G_{k,j}" + "P" + "A_{Ed}" + "\sum_{i\geq 1} \psi_{2,i}Q_{k,i} \tag{2}$$

It is easy to see that in the composition of this combination equation we distinguish 2 secondary equations: on the one hand, the mass grouping equation and, on the other hand, the seismic action equation.

By discretization we obtain the form of the 2 equations, as follows:

Mass grouping equation:

$$\sum_{j\geq 1} G_{k,j}" + "\sum_{i\geq 1} \psi_{2,i}Q_{k,i} \tag{3}$$

Seismic action equation (S.R.S.S. modal superposition):

$$A_{Ed} = \begin{Bmatrix} E_{Edx} + 0{,}3E_{Edy} + 0{,}3E_{Edz} \\ 0{,}3E_{Edx} + E_{Edy} + 0{,}3E_{Edz} \\ 0{,}3E_{Edx} + 0{,}3E_{Edy} + E_{Edz} \end{Bmatrix} \tag{4}$$

where:

A_{Ed} = seismic action, action that occurs due to the movement of the ground in an earthquake;

$E_{Edx}, E_{Edy}, E_{Edz}$ = design effects in all three orthogonal directions due to earthquake ground motion.

As can be seen, for obtaining the modal overlap in the previous descriptions, the emphasis is on the S.R.S.S (root of the sum of squares of the modal responses) probabilistic combination method.

As can be seen from this chapter, the combination equation for the seismic design of buildings is exclusively associated with the modal method through response spectra, presented in detail in P100/1-2013, ch.4.5.3.3. In all other situations when a seismic calculation based on simplifying assumptions is desired, the principles of equation 6.12 (a) & (b) from SR EN 1990 can no longer be applied. The application of the statically equivalent forces method will be used, which automatically assumes the modeling of the effect of the action seismic through distributions of static forces associated with each level of the building (P100/1-2013, chap. 4.5.3.2).

As a result, also in the case of anti-earthquake design of buildings, there is the possibility of using both calculation approaches based on the modeling of seismic ACTION, and approaches that assume the direct quantification of EFFECTS. The decision to adopt one of the stated methods is the responsibility of the structural engineer, the criteria that impose one method or another depending on aspects such as: the complexity of the structure, its configuration in plan and elevation and, finally, the distribution of stiffnesses.

3. EARTHQUAKE AS AN EFFECT IN THE DESIGN OF SILOS

[SR EN 1990, SR EN 1998-4 AND SR EN 1991-4]

The synthetic presentation of the stages of seismic damage to buildings made in the previous chapter was necessary to emphasize how important it is to find alternative methods of seismic design for less common types of constructions, a category in which silos and tanks can easily be included. The need is all the greater since, in Romania, since the first part of the national seismic design code appeared in 2013, part IV intended for the seismic design of silos and tanks has not been published.

For this reason, in design practice, for silos, it becomes extremely difficult to establish the theoretical foundations that can be used to obtain an effective seismic calculation method. The problem becomes even more complex when the overall stiffness of the silos is lower, i.e., when the slenderness of the resistance structure has an important influence on the overall behavior. Slenderness has a decisive role in the behavior of the structure of the silos, but also a decisive role regarding the type of analytical model that must be chosen to obtain an appropriate behavior resulting in correct efforts and displacements, without peaks in the measurements.

In accordance with SR EN 1991-4 - "Actions on structures. Silos and Tanks”, slenderness is presented as a decisive term for the assessment of loads on the vertical walls of silos. Thus, the loads on the vertical walls of the silos will be evaluated according to the slenderness of the silo, aiming at the following classes:

- *slender silos:*

$$2.0 \leq {}^{h_c}/_{d_c} \tag{5}$$

- *silos with intermediate slenderness:*

$$1.0 < {}^{h_c}/_{d_c} < 2.0 \tag{6}$$

- *flattened silos:*

$$0.4 < {}^{h_c}/_{d_c} < 1.0 \tag{7}$$

- *retention silos:*

$${}^{h_c}/_{d_c} \leq 0.4 \tag{8}$$

The previous statements become very important in the context of the current design activity, where most dimensioning calculations are performed on three-dimensional analytical models created with the help of automatic calculation programs that use the finite element method (F.E.M.). As an example, if the dimensioning of a retention silo is required, then the seismic calculation can be performed using the modal method through response spectra similar to buildings (detailed in chapter 2), the slenderness effect being negligible in the context of the structure's response; if the dimensioning of a slender or intermediate slenderness silo is required, it is recommended that the seismic analysis be carried out using the dynamic pressures determined with the help of SR EN 1998-4, the slenderness effect being an essential component in the interpretation of the structure's response.

The modal method through response spectra applied to silos assumes, like buildings, the conversion of the action of the granular material into mass, which, in a later stage, will be associated with the wall through springs with stiffness Kc, determined according to the material constants (Figure 3).

Although the method is apparently accessible and allows easy modeling with calculation programs (F.E.A.), it has the great disadvantage that the application of the masses is done pointwise on the silo wall, at the point of application of the resulting dynamic pressure diagram. In other words, when the situation requires the design of a slender silo or with intermediate slenderness, the mass being applied pointwise on the surface of the wall, erroneous maximum values for stresses, deformations and displacements near the application points will be obtained, values that cannot lead to a proper assessment of the strength and stability of the structural system.

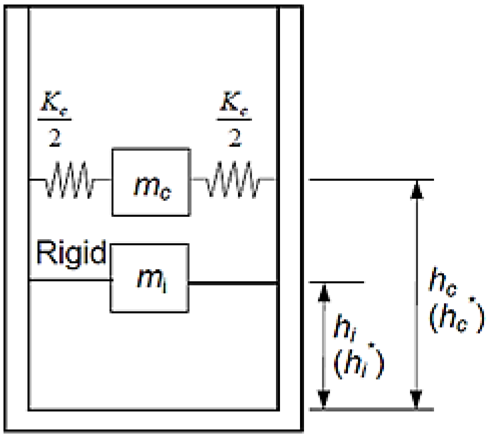

Fig. 1 The composition schema of the model by the modal method

The seismic calculation method that involves the use of the normal pressure given by the silage material is presented in SR EN1998-4, sec.3.3, as an alternative to the spectral method, stated previously. Indeed, the method can be considered as semi-precise because it does not propose to consider, explicitly, the mechanical properties and the dynamic response of the granulated material, that is, it does not use finite elements to model the mechanical properties and the dynamic response of the silage material. In this way, the method proposes the direct modeling of the effect on the mantle given by the response of the granular material to the horizontal component of the seismic action. The response of the stored material will be represented by a normal additional pressure (overpressure) with the following expressions:

- *for circular silos:*

$$\Delta_{ph,s} = \Delta_{ph,so}\, cos(\theta) \tag{9}$$

where:
$\Delta_{ph,s}$ = reference pressure.
θ = angle between the radial direction of an analyzed point on the wall and the direction of the horizontal component of the seismic action.

- *for rectangular silos:*
    - wall „under wind”:

$$\Delta_{ph,s} = \Delta_{ph,so} \tag{10}$$

    - wall „in wind":

$$\Delta_{ph,s} = -\Delta_{ph,so} \tag{11}$$

    - wall parallel to the horizontal component of the seismic action:

$$\Delta_{ph,s} = 0 \tag{12}$$

At points on the silo wall located at a vertical distance x from the horizontal (flat) bottom or the top of a conical or pyramidal funnel, the reference pressure $\Delta_{ph,so}$ has the expression:

$$\Delta_{ph,so} = \alpha_{(z)}\gamma\, min(r_s; 3x) \tag{13}$$

where:

$\alpha_{(z)}$ = the ratio between the response acceleration of a silo, at a vertical distance z from the equivalent surface of the stored material, and the gravitational acceleration.

$$r_s = min\left(h_b; {}^{d_c}/_2\right) \tag{14}$$

in which:

h_b = the overall height of the silo, measured from the flat bottom or hopper outlet to the equivalent area of the stored contents.

d_c = the internal dimension of the silo parallel to the horizontal component of the seismic action (the internal diameter for circular silos or the internal horizontal dimension parallel to the horizontal component of the seismic action for rectangular ones).

For silos where the material is discharged through the funnel, the reference pressure between the skirt and the discharge hole is calculated with the relation:

$$\Delta_{ph,so} = \alpha_{(z)}\gamma\, min(r_s; 3x)/\, cos(\beta) \tag{15}$$

in which:

β = angle of inclination of the wall of a silo, measured from the vertical, or the angle of the line of greatest slope from the vertical of the wall of a pyramidal hopper.

To perform the calibration of the alternative analytical model, SR EN 1998-4 indicates, through paragraphs (11) and (12), two rules:

(i) at no point on the silo wall the sum of the static pressure of the granulated material and that of the effect of the seismic action Δph,s shall not be less than zero;

(ii) if at any point on the silo wall the sum of $\Delta_{ph,s}$ and the static pressure of the granulated material on the wall is negative (clearly implying a suction) then the above relations cannot apply. In this situation, the additional normal pressures on the wall $\Delta_{ph,s}$ are redistributed to ensure that their sum with the static pressure of the granular material on the wall is still positive, keeping the same resultant force on the same horizontal plane as the values of $\Delta_{ph,s}$.

By deepening the alternative seismic calculation method specific to silos and from the design experience accumulated on this type of structures, we encountered important difficulties in determining the parameter $\alpha_{(z)}$, an aspect largely due to the lack of content of the Eurocode.

Therefore, in this article, I propose my own interpretation of how to determine $\alpha_{(z)}$, starting from the very definition of the term extracted from SR EN 1998-4, sec.3.3, art.8, rel. (3.5).

Therefore, the equation that can define the term $\alpha_{(z)}$ takes the following expression:

$$\alpha_{(z)} = \frac{K_z a_g}{g} \tag{16}$$

where:

$K_z =$ coefficient representing the amplification of the seismic acceleration of the land on the height of the construction;

$a_g =$ design ground acceleration (for the horizontal component of ground motion), for which two relations are presented below:

- *according to SR EN 1998-1, chap.3.2.2.2., rel. (3.2) ÷ (3.5):*

$$a_g = \gamma_i a_{gR} \tag{17}$$

where:

$\gamma_i =$ importance factor.

$a_{gR} =$ the peak value of the reference maximum acceleration for terrain type A.

- *according to P100/1-1992:*

$$a_g = K_s \mathrm{g} \tag{18}$$

where:

$K_s =$ the ratio between the maximum acceleration of the seismic movement of the land corresponding to the seismic area of calculation and the gravitational acceleration (definition extracted from the old design standard P100/1-1992);

$g =$ gravitational acceleration.

The coefficient representing the amplification of the seismic acceleration of the ground on the height of the construction (K_z) is not explicitly defined in section 3.3 intended for the seismic calculation of silos in SR EN 1998-4, however, by analogy with the fundamental principles of seismic calculation presented in SR EN 1998-1 and taken over in P100/1-2013, the following calculation relationship can be indicated:

$$K_z = 1 + 2\frac{z}{H} \tag{19}$$

in which:

$z =$ the design height measured from the horizontal (flat) bottom or top of a conical or pyramidal funnel to the point of application of the resulting reference pressure $\Delta_{ph,so}$.

$H =$ overall height of the silo.

From the previous formulations it can be extracted the statement that the seismic response of the stored material can be easily evaluated; what remains to be determined is how to associate these effects with the other permanent and variable actions imposed, to finally obtain the design equation for the special grouping.

As noted in chapter 1 of the article, for buildings, the Fundamental Code SR EN 1990 recommends that equations 6.12(a) and 6.12(b) be used for seismic design situations. Among them, the seismic action A_{Ed} involves the evaluation by means of modal combination methods (widely discussed in chapter 2), methods that assume the conversion of all actions into masses.

With the application of the alternative method of seismic design of silos, equation 6.12 with its two parts (a) and (b) can no longer be applied, the modal evaluation being replaced by the seismic response of the stored material, i.e., the reference pressure $\Delta_{ph,s}$.

Design code SR EN 1991-4 - "Actions on structures. Silos and Tanks", in Annex A, presents the seismic combination equation as a design equation at the "seismic" ultimate limit state (SLU "Seismic"). Annex A has an essential role here because, although the main text of this part of Eurocode 1 deals with the calculation of static actions given by granulated material on the vertical walls of silos, it adapts the design equations to ultimate limit states presented as fundamental principles for buildings in SR EN 1990 - aspect extracted from the very title of Annex A: "Basics of design - additional paragraphs to EN 1990 for silos and tanks".

SR EN 1991-4 presents the combination key for the combination equation in special grouping in table A.4: "Seismic" ultimate limit state (SLU "Seismic") - design situations and groups of loads to be considered, extracted from Table 1.

Table 1 (A.4) – "Seismic" ultimate limit state (SLU "Seismic") - design situations and load groupings to be considered

Sym-bol	**Design Situation/ Principal Variable Load**	**Permanent loads**		**The main variable load**		**Additional variable load 1 (basic)**		**Additional variable load 2**		**Additional variable load 3,4, etc.**	
		Descrip-tion		Descrip-tion		Descrip-tion	$\boldsymbol{\psi}_{1,1}$ or $\boldsymbol{\psi}_{1,1}$	Description	$\boldsymbol{\psi}_{2,2}$	Descrip-tion	$\boldsymbol{\psi}_{2,3}$ $\boldsymbol{\psi}_{2,4}$
SF	Seismic loading and full silo	Self-weight		Seismic loading (earth-quake)		Material filling, full silo	**0,8**	Imposed deformation	**0,3**	Variable loads	**0,3**
SE	Seismic loading and empty silo	Self-weight		Seismic loading (earth-quake)		No materials, empty silo	**0,8**	Imposed deformation	**0,3**	Variable loads	**0,3**
NOTE: **Table 1** (A.4) is used together with expression (6.12b) from SR EN 1990, 6.4.3.4 and those from SR EN 1998-1 and SR EN 1998-4											

Thus, the design equation for the seismic ultimate limit state has the expression:

$$\sum_{j>1} G_{k,j}" + "\left(P_h + \Delta_{ph,s}\right)" + "\sum_{i>1} \psi_{2,1} Q_{k,i} \qquad (20)$$

in which:

$\sum_{j>1} G_{k,j}$ = group of all permanent loads.

$\sum_{i>1} \psi_{2,1} Q_{k,i}$ = the group of all variable loads of the same nature.

$\psi_{2,1} Q_k =$ quasi-permanent value of a variable share determined so that the total period of time for which it will be exceeded represents a significant part of the reference period.

$\left(P_h + \Delta_{ph,s}\right)$ = the response of the stored material to the horizontal component of the seismic action superimposed on the normal pressure applied to the vertical walls of the silo.

Trying a comparison with equation 6.10 of SR EN 1990 used for fundamental group design:

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j}{}'' + {}''\gamma_{Q,1} Q_{k,1}{}'' + {}''\sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} \quad (21)$$

The following two important differences result:

- the elimination from the design equation at the ultimate seismic limit state of the partial participation factors ($\gamma_{G,j}$ and $\gamma_{Q,i}$) that accompany, in the fundamental grouping equation, both permanent loads and all variable loads,
- in the design equation at the ultimate seismic limit state, when it comes to effects, the main variable load of type "Seismic load (earthquake)" (see tab.1) is considered with its full value in each loading assumption.

The comparison between the two equations shows the important simplifications brought by the silo effect seismic calculation method, compared to the universal design seismic spectrum method. The alternative method presented in this chapter helps to better understand the seismic behavior of silos, regardless of the slenderness class, the structural response obtained by calculation being easier to associate with the real behavior.

4. CONCLUSIONS

In conclusion, to perform seismic calculation without evaluating the seismic ACTION, in the case of silos, the European code SR EN 1998-4 proposes an alternative method of direct evaluation of the EFFECTS, more precisely of the response of the granulated material to the horizontal component of the seismic action on the silo wall. The presented alternative method is based on obtaining some seismic reference pressures $\Delta_{ph,s}$, which through the principle of superposition are composed with the normal pressure applied on the vertical walls of the silo (P_h).

The determination of the seismic pressure will be made on relative heights measured from the flat bottom or from the discharge hole towards the top, finally, on the elevation, obtaining a parabolic type of variation. The parabolic variation of the pressure diagram is given, on the one hand, by the equation of the Janssen form entering into the calculation of the normal static pressure and, on the other hand, by the ratio of the response acceleration at a vertical distance z to the equivalent surface of the stored material and the gravitational acceleration ($\alpha_{(z)}$), component of the reference pressure.$\Delta_{ph,s}$.

Consequently, the alternative seismic method will require that the design assumption combination equation be performed according to Annex A.4. - "Seismic ultimate limit state" (SLU "Seismic") - design situations and groups of loads that must be considered" from SR EN 1991-4 - widely discussed in chapter 3.

Although the method of seismic calculation through the evaluation of EFFECTS is presented by SR EN 1998-4 as an alternative to the modal method through response spectra, it presents a good applicability in engineering practice, reducing, on the one hand, the complexity of the analytical models that they will be the basis of the design, and, on the other hand, making the interpretation of the phenomenon accessible.

5. REFERENCES

[1] Roberts, A.W., (1994), *Developments in silo design for the safe and efficient storage and handling of grain*, Proceedings of the 6th International Working Conference on Stored-Product Protection, CAB International and Wallingford, United Kingdom

[2] Nateghi, F. and Yakhchalian, M., (2011), *Seismic behavior of silos with different height to diameter ratios considering granular material-structure interaction*, Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology, Tehran, Iran

[3] Georgiev Ginko, Sverige AB Reinertsen, (2013), *A seismic evaluation of SFR - Analysis of the Silo structure for earthquake load*, Swedish Nuclear Fuel and Waste Management Co – SKB

[4] Silvestri S., Trombetti T. And Gasparini G., (2008), *Flat-bottom Grain Silos under Earthquake Ground Motion*, The 14th World Conference on Earthquake Engineering, Beijing, China

[5] SR EN 1998-1, Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings

[6] SR EN 1998-4, Eurocode 8: Design of structures for earthquake resistance. Part 4: Silos, tanks and pipelines

[7] SR EN 1990, Eurocode: Basics of structural design/SR EN 1990/NA: Eurocode: Basics of structural design. National Annex

[8] SR EN 1991-4, Eurocode 1: Actions on structures. Part 4: Silos and tanks

[9] Markus Kettler, (2008), *Earthquake Design of Large Liquid-filled Steel Storage Tanks – Comparison of present design regulations, load carrying behavior of storage tanks*, VDM Verlang Dr.Muller A.&Co

[10] NICEE and Indian Institute of Technology Kanpur, (2007), *GSDMA Guidelines for Seismic Design of Liquid Storage Tanks – Provisions with commentary and Explanatory Examples*

[11] Bond A. And Harris A., (2008), *Decoding Eurocode 7*, Taylor and Francis, London and New York

[12] Rotter M.J. and Schmidt H., (2013), Buckling of Steel Shells European Design Recommendations – N^{o}125, 5th Edition, revised for second impression, ECCS – European Convention for Constructional Steelwork

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