PARAMETRIC STUDY OF THE SEISMIC RESPONSE OF ANCHORED METALLIC TANKS BY INTERNATIONAL DESIGN CODES

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ABSTRACT :

The present work addresses the synthesis of the research on tank lifelines that as been successfully addressed at FEUP School of Engineering of the University of Porto. Some actual regulatory design provisions for anchored tanks are compared in dimensionless graphs of design quantities (basal shear, basal moments) evaluated using American Petroleum Institute API 650, Indian Standard IS 1893 and Eurocode EC8. Some conclusions about these specific design provisions are outlined.

KEYWORDS: Seismic design of tanks, Code provisions for tanks, Fluid-structure interaction.

1. INTRODUCTION

Due to continuing damage and failure of liquid storage tanks during major earthquakes of 1960's and 1970's, earlier simplified methods for their seismic analyses were questioned. Veletsos and Yang [1] reformulated the models then existent and proposed an improved model using a new component (besides the impulsive and the convective) taking into account the dynamic fluid structure interaction (FSI) of the liquid with the structure of the tank (that translates the flexibility of the walls of the tank). This is illustrated directly in Figure 1 by the additional mass (m_f) accounting for FSI. The convective component of the response is not altered, and could continue to be calculated in a manner similar to the original simpler formulation of Housner.

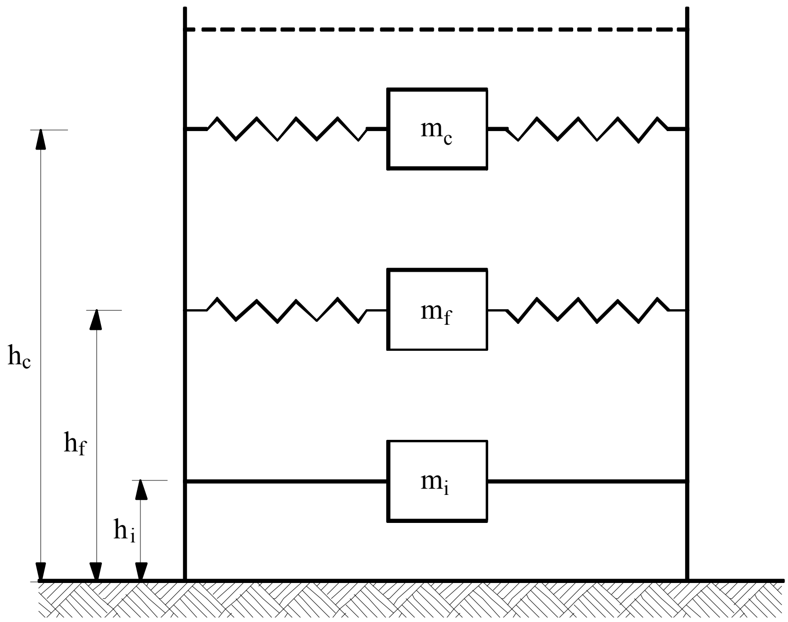

Figure 1 – Model proposed by Veletsos and also included in last version of EC8

Therefore based on distinct rigid/flexible beam methodologies for bottom supported tanks, as comprehensively exposed by Veletsos [2] and also comparatively applied by Barros [3] to the Caucete's tanks damaged by the San Juan earthquake of November 1977, it was possible to create design standards and regulations that incorporate the seismic response and design of tanks in a quite simplified but accurate way.

Herein it is included a study of three design codes (American Petroleum Institute API Standard 650 [4], Indian Standard Seismic Code IS 1893 [5] and Eurocode EC8 [6]), accomplishing a comparative parametric analysis of some design quantities associated with the mentioned regulations.
For coherence and completeness the three different response components are commonly labelled: "*i*" denoting impulsive, "*c*" denoting convective, and "*f*" or "*d*" denoting flexibility (or dynamic FSI). The latter is therefore an impulsive effect of FSI, associated with the tank flexibility.
For the purpose of the present parametric analysis, the seismic zone factors of the (north-American , Indian and European) seismic zoning scenarios were extrapolated as valid in Portuguese territory as well, so that the assessment and parameterization is done for the same tank at same location with the most unfavorable limit values. The obtained results (basal shear, basal moment, overturning moment and maximum amplitude of the sloshing wave) were represented in graphical forms [3, 7] that allow, through simple interpolations, either verification of the seismic design of standard existing tanks or the selection of geometric design parameters for new tanks. The basal moment controls the occurrence of the elephant-foot bulge, while the maximum amplitude of the sloshing wave (controlling the required tank freeboard) corresponds to the maximum liquid surface displacement (in the vertical direction) measured from the original undisturbed liquid surface. Because of limitations of space, only the basal shear and basal moment will be addressed and compared herein, but the remaining data of the parametric study was published by Barros [3, 7].

2. SEISMIC DESIGN OF TANKS BY API STANDARD 650

The American code for design of steel tanks from the American Petroleum Institute (API 650 [4]) is based upon another American code for structures in general (Uniform Building Code UBC), after a compatible simple and efficient adaptation done by Wozniak and Mitchell [8] of the continuing theoretical developments of Veletsos and his R&D collaborators (Veletsos [2]).
API 650 uses the static method of evaluating seismic effects, in which the structures are designed to equivalent static forces substituting the dynamic earthquake forces. In this code the tank response is evaluated with the two components ("*i*" impulsive and "*c*" convective), without any account for the additional impulsive effect of FSI ("*f*" flexibility). Also only the fundamental sloshing vibration (of the liquid inside the shell) is considered, since it is the one that major contributes to the tank dynamic response (Barros [3, 7]). Wherever appropriate the expressions were coherently adapted, from the original document, for being able to be used only in SI units.
The basal shear V_{basal} and basal moment M_{basal}, overturning moment M_{overt} and maximum amplitude of the sloshing wave d_{max} are given respectively by

$$V_{basal} = Z.I\left(C_i.W_s + C_i.W_r + C_i.W_i + C_c.W_c\right) \tag{1}$$

$$M_{basal} = Z.I\left(C_i.W_s.h_S + C_i.W_r.h_r + C_i.W_i.h_i + C_c.W_c.h_c\right) \tag{2}$$

API 650 [4] divides USA in five seismic zones, each one with a specific seismic zone factors *Z*. The importance factor *I* is 1,0 for tanks with normal utilization, and is 1,25 for tanks either to be used in emergency post-earthquake situations or for tanks storing toxic/explosive substances located in zones where a major damage would cause significant public health problems. The lateral earthquake coefficient for impulsive forces, C_i, is herein taken as 0,60. The lateral earthquake coefficient for convective forces, C_c, is determined by one of two expressions, depending on the natural period T_c of the first sloshing mode, and on the soil site coefficient *S*.
For short tanks, when tank height of liquid *H* to tank diameter *D* ratio $H/D<0.75$, the weights of the impulsive and convective masses, W_i and W_c, in terms of the total weight of the contained liquid W_T, are given by appropriate expressions. Also the heights locating the impulsive and convective masses for the evaluation of the basal moment, h_i and h_c, or for the evaluation of the overturning moment, h'_i and h'_c, are given in terms of the height of liquid in the tank *H*, respectively by another set of appropriate expressions. Similar considerations apply for tall tanks ($H/D>0.75$). But the convective quantities, directly associated with the sloshing of the contained liquid, are considered not to be affected by the tank aspect ratio *H/D*. The weights of the impulsive masses of the shell (subscript *s*) and of the roof (subscript *r*), W_S and W_r , and the corresponding heights of their centers of gravity, h_s and h_r are determined on the basis of the tank geometric properties [3, 7].

3. SEISMIC DESIGN OF TANKS BY INDIAN STANDARD SEISMIC CODE (IS 1893)

The Indian standard IS 1893 [5] presents significant changes with respect to earlier versions, definitely influenced by other existing codes namely: API Standard 650, ACI 350, FEMA 368 and EC8. The evaluation of impulsive and convective masses and heights of their locations is done in a similar manner as the one also used for API 650, and also depends on the tank aspect ratios. The calculation of natural periods for the impulsive and convective modes of vibration is done in a similar manner as the one used in EC8 [6].

The coefficients of time period for impulsive and convective modes, C_i and C_c, depend on the aspect ratios H/D. The impulsive and convective natural periods of the impulsive and convective modes, T_i and T_c, are given by expressions dependent on the thickness t of tank wall, the modulus of elasticity E of tank wall, and the mass density ρ_l of the contained liquid [3, 5, 7].

Damping in the convective mode for all types of liquids and for all types of tanks shall be taken as 0.5% of the critical. Damping in the impulsive mode shall be taken as: 2% of the critical for steel tanks; 5% of the critical for concrete or masonry tanks.

The design horizontal seismic coefficient A_h is calculated separately for impulsive and convective modes. It is given in terms of the average response spectral acceleration S_a (or in terms of the response acceleration coefficient S_a /g) by

$$A_h = \frac{Z}{2}\frac{I}{R^*}\frac{S_a}{g} \tag{3}$$

in which Z is the seismic zone factor and the importance factor I (1,0 or 1,5) depends on the use of the tank.

The importance factor I is 1,5 for tanks either to be used in post-earthquake situations or for tanks storing drinking water, toxic/explosive substances (including non-volatile material and low inflammable petrochemicals) and water for emergency fire-fighting situations. The importance factor I is 1,0 for all other tanks with no risk to life and with negligible consequences to environment, society and economy.

The response reduction factor R^* depends on the type of connection to the ground. For steel tanks with anchored bases the response reduction factor equals 2,5. The response acceleration coefficient S_a /g, depends on the type of soil at the tank location site and on the period T (impulsive or convective). Generally it is constant for short periods, and decreases hyperbolically for higher periods [3, 5, 7].

The impulsive and convective masses (m_i and m_c) in terms of the total mass of the contained liquid m_l, the heights locating the impulsive and convective masses (h_i and h_c) for the evaluation of the basal moment, as well as the heights locating the impulsive and convective masses (h'_i and h'_c) for the evaluation of the overturning moment, are given by expressions dependent on the aspect ratio H/D.

The Indian standard IS 1893 evaluates for each response component (impulsive and convective) the maximum basal shear V_{basal}, maximum basal moment M_{basal}, and maximum overturning moment M_{overt}. Thereafter the total value of each design quantity (basal shear, basal moment and overturning moment) can be obtained by combining the maximum values of each quantity in impulsive and convective modes, through standard Square Root of Sum of Squares (SRSS) rule [3, 5, 7].

The impulsive, convective and total basal shears are calculated from:

$$\left.\begin{aligned} V_i &= A_{h,i}\left(m_s + m_r + m_i\right)g \\ V_c &= A_{h,c}.m_c.g \\ V_{basal} &= \sqrt{V_i^2 + V_c^2} \end{aligned}\right\} \tag{4}$$

The impulsive, convective and total basal moments are calculated from:

$$\left.\begin{aligned} M_i &= A_{h,i}\left(m_s h_s + m_r h_r + m_i h_i\right)g \\ M_c &= A_{h,c}.m_c.h_c.g \\ M_{basal} &= \sqrt{M_i^2 + M_c^2} \end{aligned}\right\} \tag{5}$$

4. SEISMIC DESIGN OF TANKS BY EUROCODE 8 (EC8)

The procedure used in the EC8 [6] is based upon the already mentioned work of Veletsos [1, 2] with possibility of some modifications that turn it simpler and of more widespread application. In the actual version of the EC8 fluid structure interaction (FSI) is accounted for directly, following the works of Haroun and Housner [9] and Fischer et al. [10]. However the FSI component does not enter directly in the simplified procedure for fixed based cylindrical tanks, also allowed by EC8 [6] in view of the works of Malhotra et al. [11], as will be emphasized latter in the parametric analysis. For practical applications, it is reasonable to just account for the first mode of vibration of each one of the components (convective, due to liquid sloshing; and dynamic FSI, due to tank flexibility) since they mobilize for most of the tanks (with aspect ratio height/radius in the range: 0,3 <H/R <3) about 85% to 98% of the total mass of the contained liquid. For tall tanks, the remaining liquid mass vibrates essentially in higher impulsive modes above the first mode. For short tanks, the remaining liquid mass mobilizes the higher vibration modes of the convective response [3, 7].
Firstly, the mass of the tank shell wall m_w, the mass of the roof m_r and the mass of the contained liquid m_l are calculated, and the corresponding heights of their centers of gravity, h_w and h_r, are determined on the basis of the tank geometric properties. Then the impulsive (m_i), convective (m_c) and flexibility or dynamic FSI (m_f) masses can be estimated from appropriate mass ratios, given in tabular or graph forms, by:

$$\left.\begin{aligned} m_i &= (m_i / m_l).m_l \\ m_c &= (m_c / m_l).m_l \\ m_f &= (m_f / m_l).m_l \end{aligned}\right\} \tag{6}$$

The heights locating the impulsive (i) convective (c) and flexibility or dynamic FSI (f) masses, (h_i, h_c, h_f) and (h'_i, h'_c), for calculating respectively the basal moment and the overturning moment, can be estimated from appropriate mass ratios in tabular (Table 1) or graph forms, by:

$$\left.\begin{aligned} h_i &= (h_i / h_l).h_l \\ h_c &= (h_c / h_l).h_l \\ h_f &= (h_f / h_l).h_l \end{aligned}\right\} \text{ and } \left.\begin{aligned} h_i' &= (h_i' / h_l).h_l \\ h_c' &= (h_c' / h_l).h_l \end{aligned}\right\} \tag{7}$$

Table 1 – Mass ratios, height ratios and period coefficients, for various aspect ratios

H/R	C_i	C_c	m_i/m_l	m_c/m_l	m_d/m_l	h_i/h_l	h_c/h_l	h_d/h_l	h_i'/h_l	h_c'/h_l
0.3	9.28	2.09	0.176	0.824	0.150	0.400	0.521	0.480	2.640	3.414
0.5	7.74	1.74	0.300	0.700	0.200	0.400	0.543	0.420	1.460	1.517
0.7	6.97	1.60	0.414	0.586	0.313	0.401	0.571	0.431	1.009	1.011
1.0	6.36	1.52	0.548	0.452	0.380	0.419	0.616	0.450	0.721	0.785
1.5	6.06	1.48	0.686	0.314	0.420	0.439	0.690	0.475	0.555	0.734
2.0	6.21	1.48	0.763	0.237	0.442	0.448	0.751	0.498	0.500	0.764
2.5	6.56	1.48	0.810	0.190	0.430	0.452	0.794	0.523	0.480	0.796
3.0	7.03	1.48	0.842	0.158	0.419	0.453	0.825	0.530	0.472	0.825

The natural periods (T_i, T_c and T_f) of the impulsive convective and flexibility components of seismic response are evaluated [4] from the coefficients of time period for impulsive and convective modes – C_i (dimensionless) and C_c (expressed in: s/√m) – and from the following set of variables: aspect ratio H/R, stiffness parameter t/R, E modulus of elasticity of the tank wall, t thickness of the tank wall at about one-third of its wall height (i.e., at $H/3$) and the mass density ρ_l of the contained liquid [3, 6, 7]. With all the previous information, a combination of the distinct shear and moment terms due to horizontal earthquake excitation can be accomplished in the time-domain. But although individual maxima of the terms in such equation could be achieved by using response spectra of absolute accelerations and of relative accelerations (if known), thereafter lies the problem of how to superimpose such maxima. While the rule of the square root of the sum of squares rule is un-conservative, the simple addition of the individual maxima can lead to over-conservative estimates [3, 7].

EC8 [6] tries to overcome these difficulties by allowing various approximate approaches namely the ones of Veletsos-Yang (VY) [1, 2], of Haroun-Housner (HH) [9] and the simplified procedure of Malhotra (M) [11]. For the purpose of comparing results obtained by the 3 codes (API 650, IS 1893, EC8) the simplified procedure of Malhotra for fixed base cylindrical tanks is used herein. Using a response spectra approach, the maximum total basal shear and maximum basal moment using the simplified procedure of Malhotra et al [11] (that does not account for FSI due to tank flexibility) are calculated by:

$$\left.\begin{aligned} V_{basal} &= (m_i + m_w + m_r).S_e(T_i) + m_c.S_e(T_c) \\ M_{basal} &= (m_i.h_i + m_w.h_w + m_r.h_r).S_e(T_i). + m_c.h_c.S_e(T_c) \end{aligned}\right\} \quad (8)$$

where $S_e(T_i)$ is the impulsive spectral acceleration obtained from a 2 percent damped elastic response spectrum for steel, and $S_e(T_c)$ is the convective spectral acceleration obtained from a 0,5 percent damped elastic response spectrum. These spectral accelerations are evaluated, for earthquakes of type I and II, by the EC8 formulation for the four zones in the spectrum associated with three reference periods (with five soil site coefficients *S*).

5. PARAMETRIC STUDY OF DESIGN SEISMIC ACTIONS ON ANCHORED METALLIC TANKS

5.1. Organization of the parametric study

In order to make a parametric analysis the most universal and useful possible, some relative ratios or dimensionless variables were obtained from the original generalized actions calculated. The dimensionless character of the technical design quantities – basal shear, basal moment and overturning moment – was achieved by a normalization method either dividing the shears by the total weight of the tank, or dividing the moments by the product 'weight of tank x tank radius'. The dimensionless generalized actions constitute the base for the elaboration of universal graphs, which constitute a normalized output of the parametric analyses.
Also, the parametric results were obtained in function of two fundamental geometric relationships: the aspect ratio between the height of the tank and the radius of tank *H/R* (or *H/D*) and the ratio between the radius of tank and the average thickness of the shell wall *R/t* (or *D/t*). While the former represents a relationship of geometric structural slenderness, the latter is directly linked to the stiffness of the tank wall [3, 7].
Several tank analyses were done varying the geometric relationships defined previously in order to cover a wide range of commercial tanks, and still facilitating interpolation of results for tanks with geometries different from those studied. Table 2 synthetically presents the characteristics of the range of 75 tanks that were used in this parametric study. The results presented herein will typically show the graphs of the design quantities involved corresponding to tanks 10 m and 30 m tall, with the above mentioned parametric variation of characteristics.

Table 2 – Characteristics of tanks for the parametric study

H (m)	H/R	R/t
10 , 20 , 30	1/3 , 2/3, 3/3, 4/3 , 5/3	1920 – 1440 – 960 – 720 – 480

5.2. Graphs of results obtained using API 650 and IS 1893

Figure 2 shows the normalized parametric results for a 30 m tall tank, designed according to API 650 [4]. These results of the design quantities (normalized basal shear , normalized basal moment) do not show any variability with the tank stiffness parameter *R/t* ; this trend was coherently found for all 75 tanks analyzed with heights of 10, 20 and 30 m, since the expressions of API 650 do not have any variability with the stiffness parameter *R/t*.
Normalized parametric results were also obtained for a 30 m tall tank, designed according to IS 1893 [5]. The mentioned technical design quantities (normalized basal shear, normalized basal moment, and normalized overturning moment) do not show, in normalized form, any significant variability with the tank stiffness parameter R/t. This trend was found for all 75 tanks analyzed with heights of 10, 20 and 30 meters, and in fact is coherent since the expressions of IS 1893 remain constant for the range of low analyzed periods (of these stiff tank structures). Moreover it is found that IS 1893 slightly underestimates the results of the normalized actions [3, 7] already obtained according to API 650.

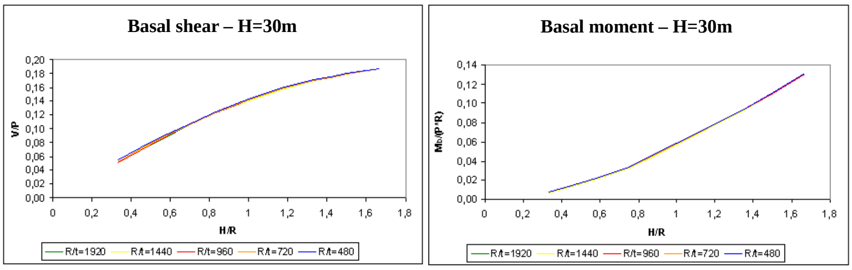

Figure 2 – Normalized actions (basal shear, basal moment), for a tank 30 m height designed using API 650

5.3. Graphs of results obtained using EC8

Figure 3 typically shows normalized parametric actions (basal shear and basal moment) with aspect ratio *H/R* for a 30 m height tank designed according to EC8 [6], used as comparison with the 30 m height tanks analyzed before by API 650 and IS 1893. These results correspond to seismic action of type II (AS-2), for which the normalized actions evaluated with EC8 are more conservative (and more exact as well in view of the theoretical background in which they are effectively based) than the ones evaluated with the other design codes.
This also means that API 650 and IS 1893 are un-conservative and less safe than EC8. Also for this 30 m height tank, the parametric study associated with seismic action of type I (AS-1) shows no significant dependency on the stiffness parameter *R/t*. For this higher dimensions tank the seismic action of type II (AS-2) besides controlling design also controls dependency on *R/t* parameter. However the situation is reversed for a 10 m height tank designed according to EC8, under seismic action of type I, since for this shallower tank this seismic action controls dependency with regard to the *R/t* stiffness parameter [3, 7].

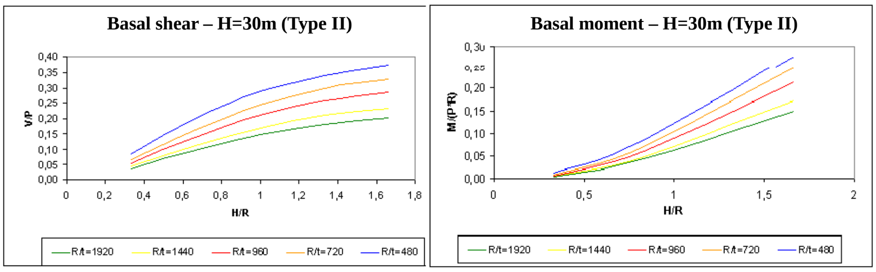

Figure 3 – Normalized actions (basal shear, basal moment) for a tank 30 m height designed according to EC8 (Seismic Action of Type II)

5.4. Comparison of the normalized actions obtained by the three Seismic Design Codes

Figures 4 and 5 show all the curves (for the 5 values of the stiffness parameter *R/t*) obtained by the 3 design codes for the variation of the normalized basal shear and normalized basal moment with aspect ratio *H/R*, respectively [3]; they correspond to 10 m height (left) and 30 m height (right) tanks.
In ascending order: the dashed lines correspond to values obtained by IS 1893 and API 650, the solid lines correspond to values obtained by EC8 (seismic action type I), and the dotted lines correspond to values obtained by EC8 (seismic action type II) [3, 7].

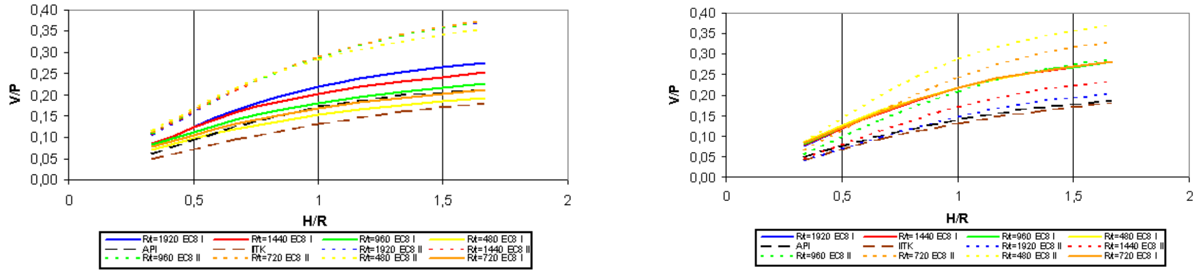

Figure 4 – Normalized design basal shear vs aspect ratio H/R for different R/t
(tank heights: 10 m, at left ; 30 m, at right)

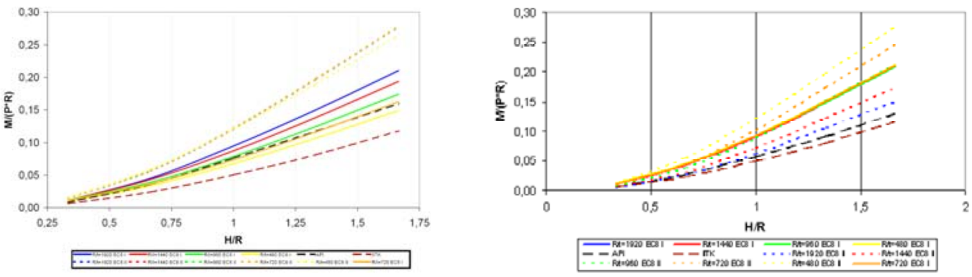

Figure 5 – Normalized design basal moment vs aspect ratio H/R for different R/t
(tank heights: 10 m, at left ; 30 m, at right)

The results obtained by API 650 and IS 1893 are rather similar, the former being more conservative than the latter. The differences are quite insignificant for taller tanks, but quite significant for shallower tanks for which they increase with increasing aspect ratio *H/R*. For unit aspect ratio, the differences are of about 30% on normalized basal shear to about 50% on normalized basal moment. With respect to the normalized results obtained with EC8, the standards API 650 and IS 1893 are un-conservative and may be unsafe in some circumstances. The differences in the normalized results, between EC8 and the other two design codes, increase with increasing aspect ratio *H/R*. For unit aspect ratio, the differences on normalized basal shear and on normalized basal moment are of about 50% for seismic action type I, to about 100% for seismic action type II. EC8 formulation is able to capture the strong dependency on the stiffness parameter *R/t*, for both types of seismic action. Therefore EC8 is a more reliable design code for design of fixed based metallic tanks [3, 7].

5.5. Relative Importance of the Impulsive, Convective and Flexibility Components

Maintaining the height of the tank, but varying the radius, the variation of the relative importance of the impulsive and convective components is practically nonexistent, as shown Figure 6 for the basal shear (dashed area refer to impulsive component, and black area refer to the convective component). The same happens, about the importance of the contributions of these components, for the basal moment and for the overturning moment.

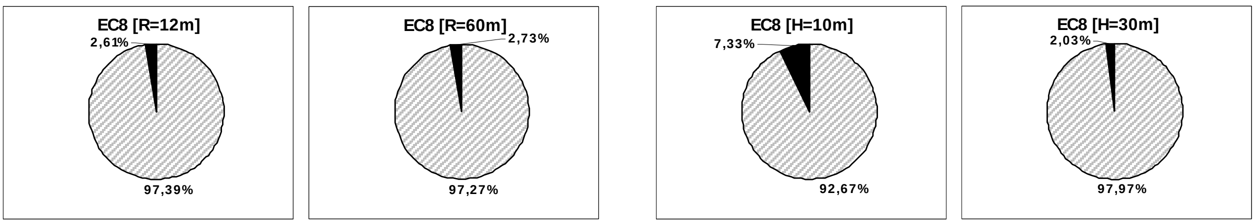

Figure 6 – Percentages of the impulsive and convective components at the basal shear determined by EC8
(varying the radius or varying the height)

An additional set of analyses were performed to ascertain the importance of the flexibility component in the quantification of normalized basal shear and of normalized basal moment [3, 7] associated with EC8 spectral formulation (Figure 7). The flexible formulation is more conservative, but relative errors are less than 10%.

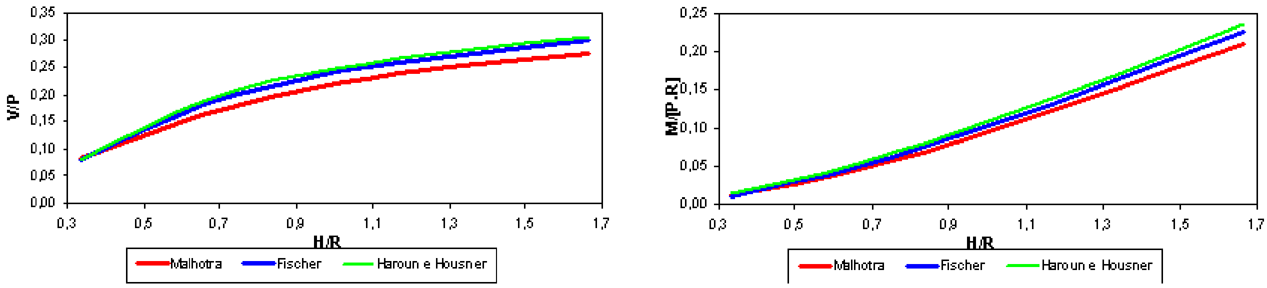

Figure 7 – Normalized dimensionless basal shear (top) and basal moment (bottom) for a 10 m height tank with aspect ratio R/t=1920, according to rigid and flexible formulations of the EC8

6. CONCLUSIONS

The provisions of three seismic design codes (API 650, IS 1893 and EC8), for seismic analysis and design of bottom supported circular tanks, were synthetically outlined and conveniently applied in a comparative parametric study of 75 tanks with specific aspect ratios *H/R* and stiffness parameter *R/t*. Normalized results of this parametric study – normalized basal shear and normalized basal moment – obtained by the three codes were compared to ascertain their relative validity. The results obtained by API 650 and IS 1893 are very similar, although they both show no dependency on the stiffness parameter and do not account for the flexibility component. They underestimate the results obtained by EC8. The latter constitutes a more reliable code standard, not only because providing higher design values according to accurate theoretical developments, but because also provides coherent dependencies with the *H/R* and *R/t* parameters of the parametric study. The relative importance of the impulsive component versus the convective component was ascertained in the variations provided by the parametric study associated with EC8 design code. The formulation of flexibility component accounted for in EC8, differs in the maximum about 10% from the same code simplified procedure.

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