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SEISMIC ANALYSIS OF STEEL STORAGE TANKS: OVERVIEW OF DESIGN CODES USED IN PRACTICE

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ABSTRACT

Seismic provision of all types of structures is of paramount importance in regions subjected to medium and high seismic hazard. This is all the more true in the case of steel storage tanks, as these often contain toxic, flammable and explosive substances or the fuels needed for post-state recovery after a catastrophic event. Additionally, steel storage tanks could be an integral part of special facilities related to national security and defence.

The current paper presents an overview of the European design codes used in practice regarding the analysis, behaviour and design of steel tanks under earthquake loading, namely EN 1998-4 (BDS EN 1998-4:2006, along with the national annex BDS EN 1998-4:2006/NA:2012) and EN 14015 (BDS EN 14015:2005). Other legislative documents – API Standard 650 and API Standard 620 are also considered. The aim of the paper is to compare the provisions provided by the aforementioned documents focusing on the aspects that require further investigation and regulation, as well as those not dealt with in the regulatory framework. Special attention is paid to the effects that a seismic event would cause to the stationary roofs of vertical cylindrical steel storage tanks.

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1. Introduction

1.1. Seismic Hazard

Every day hundreds of earthquakes shape the landscape of our Earth. According to data provided by IRIS (Incorporated Research Institutions for Seismology), more than 1 500 per year is the frequency of the seismic events that could cause possible damage to structures in the regions they occur. The number of earthquakes happening per year worldwide, their magnitude, energy release and energy equivalents, as well as some examples for major earthquakes, are presented in Fig. 1.

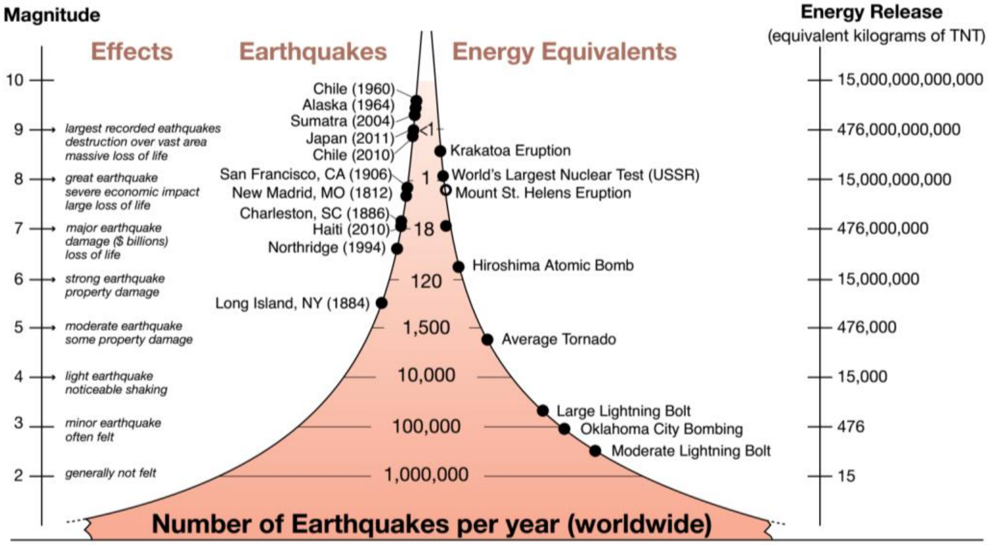

Figure 1. Number of earthquakes per year (worldwide), source: IRIS

Structures should keep their integrity during an earthquake, in order to preserve human life, avoid environmental pollution and material loss. This is why in regions with non-negligible seismic activity all structures should be designed taking into consideration such events.

1.2. Steel Storage Tanks

Special attention should be paid to the seismic design of steel storage tanks as these structures are very specific and have certain features that make their behaviour particularly different from that of a building. The storage facilities are presented by a diversity of members varying in size, shape, operational pressure and temperature, functional requirements and characteristics. Each type has its own specifications regarding analysis, design and detailing.

This article focuses on vertical cylindrical steel storage tanks. The latter are easy for fabrication, erection and maintenance and most suitable for containing large amounts of liquids. Those liquids vary from water and other substances used in the brewing, wine and food industry to the raw materials or waste products in manufacturing. Vertical cylindrical steel storage tanks present the largest share of the containers used in the petroleum and oil refining industry. Steel tanks may also be essential for the life and health of the public and for post-earthquake recovery. Eventual destruction or damage in these facilities could lead not only to material loss but also to the loss of human life and long-lasting consequences for the environment.

1.3. History of Incidents

Incidents with storage facilities around the world as a result of seismic activity are not uncommon. Some of the most severe cases happened in Chile in 1960, USA: Alaska 1964; Japan: Niigata 1964 and Tokachi in 2003. The consequences were accounted in numerous casualties, air and water pollution, infernos that could not be put down for days, financial and infrastructural losses. Lighter incidents are more common, but do not make the statistics. Even though they cause considerably less damage than major ones, their frequency is what makes them relevant.

Predicting the behaviour of the soil-tank-liquid system and the interaction between its components during an earthquake is a problem of considerable analytical complexity. For that reason, it would be highly beneficial if the structural engineer is guided through the design process by regulatory procedures and provisions.

2. Theme

The aim of this paper is to review some of the most commonly used legislative documents for seismic design of steel storage tanks and to compare the methodology, recommendations and design procedures they provide in order to point out some unclear or unregulated issues and draw a path for future development.

3. Legislative Documents

3.1. European Design Codes

In the 1970s the Commission of the European Community (presently the European Commission), initiates the development of the Eurocode standards, that later turn into a single unified system governing structural design within the European Union. The unification and compliance of the design codes, along with the technical specification of materials is crucial for ensuring the accuracy of predesign assumptions and a lifetime guarantee of adequate safety of the actual built structure.

This paper reviews only documents related to the seismic design of steel tanks, namely:

- EN 1998-4 Eurocode 8: Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines (BDS EN 1998-4:2006, along with the national annex BDS EN 1998-4:2006/NA: 2012). This document supplements EN 1991-4, EN 1993-4 and 1998-1 upon matters regarding the seismic design of facilities used for containment, transmission and processing of gas, granular, or liquid materials.

- EN 14015: Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above (BDS EN 14015:2005). Annex G: Recommendations for seismic provisions for storage tanks (informative) is of interest. Whereas EN 1998-4 is an integral part of the system of Eurocodes, EN 14015, Annex G is based on the provisions given in API 650, Annex E. This is possible since the API design code provides prescriptions for application outside of the USA. Most of the symbols used in EN 14015 are different from the ones used in Eurocode.

3.2. US Design Codes

The American Petroleum Institute (API) is the biggest national trade association representing the oil and natural gas industry in the United States of America. The organization has developed and maintains more than 680 standards and recommended practices, some of which having regulatory status. Due to the robust development of the USA's industry, especially the oil industry, tank studies and therefore standards are well presented by a variety of documents (e.g. API 12F, API 12D, API 620, API 650, AWWA D100 by the American Water Works Association).

This paper reviews:

- API Standard 650: Welded Tanks for Oil Storage, Twelfth Edition, March 2013 and specifically its Annex E: Seismic Design of Storage Tanks (normative) and Annex EC: Commentary on Annex E (informative).
- API Standard 620: Design and Construction of Large, Welded, Low-pressure Storage Tanks, Twelfth Edition, October 2013 presented by Appendix L: Seismic Design of API 620 Storage Tanks.

API 650 and API 620 follow the rules and are compliant with ASCE 7: Minimum Design Loads and Associated Criteria for Buildings and Other Structures.

3.3. Scope

3.3.1. Scope of Provisions

EN 1998-4 provides principles, application rules and additional criteria required for the seismic design of storage tanks. This standard does not give stringent limitations in regard of design pressure or operational temperature and thus covers a large group of structures, considerably different in their nature, behaviour and main characteristics. This is one of the reasons the code has only two annexes, in which specific verification rules and detailed methods of assessment are given only for certain types of tanks. In addition to the scarce application, those recommendations are not regulatory in nature, but only informative.

EN 14015, API 650 and API 620 cover limited range of tanks in regard to shape, location, fabrication, erection methods, design temperature and pressures of the stored liquids, but are considerably more thorough in their provisions. They provide recommendations and regulations for the whole process of designing a steel tank – from the technical sheet data and necessary documentation, through the requirements for the materials, design, fabrication, erection, testing and inspection of the built facility. These legislative documents are amended by a number of annexes, most of which regulatory.

The cases of floating roofs are not entirely covered neither by EN 1998-4, annex A, nor by API 650, Annex E.

3.3.2. Scope of Allowable Design Pressures and Temperatures

It is interesting to point out that although based on API 650 provisions, EN 14015 covers a larger group of structures. The maximum design pressure for tanks in the scope of EN 14015 is 500 mbar, and in API 650 it is around 180 mbar (2,5 lbf/in^2), which is nearly 3 times less. In this regard API 620 covers the largest range – up to around 1035 mbar (15 lbf/in^2) design pressure. The scope of admissible design temperatures also vary.

3.3.3. Scope of Materials

EN 1998-4 provides rules and recommendations for carbon steel structures. EN 14015, API 650 and API 620 could be applied to tanks made from materials other than carbon steel – austenitic stainless steel, duplex stainless steel, aluminium and nickel alloys. The standards also give exact specifications and requirements to the materials that could be used for fabrication of the different parts of the tanks.

3.4. Required Documentation

EN 14015, API 650 and API 620 establish the necessary documentation of a construction project – technical characteristics, design calculations, drawings as built, supplier inspection documents, material certificates, documents regarding welding, examination and testing, documentation on the supplementary systems – heating or cooling systems, safety systems, etc. EN 1998-4 does not provide such regulations.

The rights and responsibilities of all parties participating in the construction process – purchaser, steel manufacturer, tank manufacturer, cover supplier, etc. are regulated in EN 14015 and API 650. EN 1998-4 leaves some decisions in the design process to the Owner (Purchaser). In API 650 this practice is brought to a further extent. The code marks every paragraph where a decision or an action is required by the Purchaser. Furthermore, anyone who wants to make an inquiry or a proposition is welcomed to do so. The procedure and the contact information are available in API 650, Annex D: Inquiries and Suggestions for Change (informative).

4. Analysis

The special circumstance that predetermines differences in the behaviour of a storage tank compared to that of a building is the presence of liquid contained in the tank.

4.1. Analysis Methods

EN 1998-4 refers to the four methods specified in 4.3.3 [8]. The standard prescribes seismic design based on linear behaviour of the structure and the ground under the foundation unless otherwise required. It also states that in order to obtain the maximum hydrodynamic pressure induced by seismic action, the use of nonlinear dynamic (time-history) analysis is necessary. However, under certain circumstances, simplified methods with direct application of the response spectrum analysis are allowed.

EN 14015, API 650 and API 620 are based on methods using "an equivalent lateral force analysis that applies equivalent static lateral forces to a linear mathematical model of the tank based on a rigid wall, fixed based model" [3]. Dynamic analysis methods are not included within the scope of Annex E of API 650 but are permitted in lieu of the given provisions for investigation of the fluid-structure and soil-structure interaction. API 620 adopts the prescriptions given in API 650.

4.2. Model

The essential factor in modelling is the correlation between the adopted geometrical characteristics, stiffness, ductility, strength, mass and damping and the real structure.

The analysis model could be a detailed three-dimensional or a simplified one.

4.2.1. Simplified Models

It is generally accepted that the behaviour of a storage tank and its content under earthquake action could be described by two components – impulsive and convective. Further information on the methodology is given in [1], Annex A: Seismic Analysis Procedures for Tanks (informative). The "rigid impulsive" and the "sloshing" pressure components with enough accuracy represent the behaviour of a rigid tank. Alas, this is almost never the case with steel tanks. Annex A, EN 1998-4 suggests the presence of a third component, taking into account the flexibility of the tank's wall.

The other three standards use simplified provisions, considering a rigid tank fixed to the foundation.

4.2.2. Spatial Models

It is true that, given the complexity of the problem, a 3D rigorous analysis requires high efforts and computational resources, but to this day simplified provisions cannot ensure ubiquitous coverage. As an omission of all the aforementioned legislative documents could be noted the lack of regulations regarding analysis through a 3D model. The obtained results from such a model should be with higher accuracy than those obtained from the simplified models.

Although governing for silos, rule 3.2 (4) P of [1] addressing spatial analysis is not listed as applicable for steel tanks.

4.3. Damping

EN 1998-4 proposes the use of a global average damping of the whole system, taking into account the contributions of the different damping values of the components of the soil-structure-fluid system. The US design codes have adopted the same differentiation between the damped response spectra for the impulsive and for the convective mode.

In EN 1998-4, 2.3.3.2 the value for the contents damping ratio is recommended $\xi = 0.5\%$ for water and other liquids, unless otherwise determined, but in the Bulgarian translation of the code BDS EN 1998-4, 2.3.3.2 the value for the same parameter has become $\xi = 5\%$. In case there is no solid ground for this change and it is a misspelling in the translation, the value should be corrected.

4.4. Seismic Action Parameters

4.4.1. Site Ground Motion

EN 1998-4 adopts the seismic action parameters and the elastic response spectrum as regulated in [8]. The no-collapse requirement should be fulfilled in the case of a reference seismic action associated with a reference probability of exceedance, P_{NCR} = 10% in 50 years, or a reference return period, T_{NCR} = 475 years. For comparison – in [2], [3] and [4] the maximum earthquake ground motion is considered to be caused by an event with a 2% probability of exceedance within a 50-year period (a recurrence interval of approximately 2500 years). It is interesting to note that historically Annex E of API 650 was based on the same probability of exceedance and reference return period as defined in the present Eurocodes, but this approach was considered economically impractical in regions where earthquakes are less frequent (excluding the west coast of the US) and later was changed.

4.4.2. Site Ground Types

EN 1998-4 differentiates between seven ground types – from A to E, S_1 and S_2. API 650 specifies six groups: A to F and EN 14015 adopts a different approach regulating only three soil profiles – types A, B and C.

4.4.3. Reliability Differentiation Classes

EN 1998-4 distinguishes between four importance classes (I – IV), depending on the potential economic, environmental and social consequences of failure. The risk increases in an uprising manner from Class I to Class IV, IV referring to situations posing an exceptional risk.

EN 14015, Annex G does not attend such matters. API 650 differentiates between three seismic use groups, SUG III being the most stringent. The comparison between the values of the importance factors provided by the different design codes is presented in Table 1.

Table 1. Comparison between tank importance factors according to BDS EN 1998-4/NA and API 650

BDS EN 1998-4:2006/NA:2012			API 650		
Importance class	Structures	Importance factor - γ_I	SUG	Structures	Importance factor - I
I	Structures of minor importance for public safety	0,80			
II	Ordinary structures, not belonging to the other categories	1,00	I	Low risk for public safety; negligible economic and social consequences of failure	1,00
III	Structures whose seismic resistance is of importance in view of the consequences associated with a collapse	1,20	II	Medium risk for public safety and local economic or social consequences of failure	1,25
IV	Structures whose integrity during earthquakes is of vital importance for civil protection	1,60	III	Very high risk for public safety and large economic and social consequences of failure	1,50

Both regulations let the Purchaser specify the importance category of the facility.

4.5. Behaviour Factor

When determining the behaviour factor (q) for the tank, as for other structures, consideration is paid to the ability of its components to dissipate the energy accumulated by the earthquake. In the damage limitation state, elastic response is assumed (q = 1), while for ultimate limit states behaviour factors greater than 1,5 for silos and above-ground tanks are allowed, only under certain conditions. However, there is still an upper bound dictated by the type of the supporting structure (2.4, [1]).

API 650 has adopted a similar approach. Instead of using a different behaviour factor, the standard defines a response modification factor (Table E.4 [3]) that is applicable to the values of the response spectrum. Table 2 presents a parallel and a comparison between the behaviour factor used in the Eurocode system and the response modification factor regulated by API 650.

Table 2. Comparison between Behaviour Factor (EN 1998-4) and Response Modification Factors (API 650)

Design Code:	**EN 1998-4**		**API 650**	
Anchorage system	$q_{maximum}$ **(impulsive)**	q **(convective)**	R_{wi} **(impulsive)**	R_{wc} **(convective)**
Self-anchored	2	1	3,5	2
Mechanically-anchored	2,5	1	4	2

The response modification values adopted in API 650 are considerably higher than those prescribed in EN 1998-4.

5. Seismic Design

5.1. Design Combinations

EN 1998-4 gives the following provisions for combining the effects of seismic and other actions:

- Dynamic earth and groundwater pressures or the effects of connecting systems should be accounted for during the analysis, where necessary;
- The content's effects should be considered as variable loads. As a minimum requirement two levels of filling should be considered – empty and full tank. In batteries consistent of a number of tank cells, analysis of different combinations of full and empty cells is required (2.5.2, [1]).

In API 650 and API 620 every possible load combination is explicitly defined (5.2.2, [1]).

In cases of axial symmetry of the tank, only one horizontal and one vertical component of the seismic action could be analysed. In all other cases, it is necessary to take into account all three main directions. Combining the maximum effects of those components can be done by the 100% – 30% – 30% rule ([1] referring to [8]).

Combining the maximum effects of the impulsive and convective seismic response could be done by using the "square root of the sum of squares" (SRSS). In some cases, it is considered non-conservative and as an alternative rule, a sum of the absolute values of the maximums could be applied [1]. API 650, Annex E prescribes using the SRSS method unless a direct sum combination is required by the applicable regulations. Additionally, for determining the base shear, ”an alternate method using the direct sum of the effects in one direction combined with 40% of the effect in the orthogonal direction is deemed to be equivalent to the SRSS summation” [3] is proposed.

5.2. Structural periods of vibration

The simplified procedure for fixed base cylindrical tanks given in Annex A, [1] defines the natural periods of the impulsive responses, in seconds, with the expression:

$$T_{imp} = C_i \cdot \frac{\sqrt{\rho}.H}{\sqrt{s/R}.\sqrt{E}}, \tag{1}$$

where: C_i – coefficient for determining the impulsive natural period of the tank system;

H – height to the free surface of the liquid;
R – tank radius;
s – equivalent uniform thickness of the tank wall;
ρ – mass density of liquid;
E – modulus of elasticity of tank material.
All in corresponding SI units (A.3.2.2, [1]).

The formula for the same component provided by API 650, annex E is the following:

$$T_i = \left(\frac{1}{\sqrt{2000}}\right).\left(\frac{C_i.H}{\sqrt{\frac{t_u}{D}}}\right).\left(\frac{\sqrt{\rho}}{\sqrt{E}}\right), \tag{2}$$

where: *D* – nominal tank diameter, m ;

t_u corresponds to *s* from equation (1), mm and
C_i ; *H*, m; ρ, kg/m^3 and *E*, MPa have the same meaning in both formulas.

After substitution of *D* with 2*R*, it becomes clear that the formulas provided by EN 1998-4 and API 650 are the same.

In EN 1998-4 the natural period of the convective response, in seconds, is defined as:

$$T_{con} = C_c.\sqrt{R}, \tag{3}$$

C_c being a coefficient for determining the convective natural period of the tank system and *R* – the tank radius, m.

The equation prescribed by API 650 for the convective period is:

$$T_c = 1{,}8.K_s\sqrt{D}. \tag{4}$$

The sloshing period coefficient K_s is defined as:

$$K_s = \frac{0{,}578}{\sqrt{\tanh\left(\frac{3{,}68.H}{D}\right)}}. \tag{5}$$

If (5) is substituted in (4) the formula presented in API 650 could be expressed by:

$$T_c = C_c^* . \sqrt{R}. \tag{6}$$

$$C_c^* = \frac{1,471}{\sqrt{\tanh\left(\frac{3,68.H}{D}\right)}}. \tag{7}$$

In this case the prescriptions of EN 1998-4 and API 650 could be compared. The results presented in Table 3 show that the differences are negligible.

Table 3. Comparison between *Cc* coefficient values according to EN 1998-4 and API 650

EN 1998-4		API 650	
H/R	***Cc***	***Cc****	***D/H$_T$***
3,0	1,48	1,47	0,67
2,0	1,48	1,47	1,00
1,0	1,52	1,51	2,00
0,5	1,74	1,73	4,00
0,3	2,09	2,08	6,67

5.3. Effective masses and heights

Table A.2 [1] presents the impulsive (m_i) and convective (m_c) masses as fractions of the total liquid mass. Respectively h_i and h_c represent the heights at which the impulsive and convective wall pressure resultants are acting, measured from the base of the tank. API and EN 14015 provide formulas and graphics for direct determination of the aforementioned characteristics.

Table 4 presents a comparison between the values for these parameters obtained by the referred design codes. The signature follows the standards' regulations. The differences between the calculated masses vary between 3% and 8% and the deviation in the calculated heights is between 2% and 14%, depending on the height to radius ratio of the tank.

Table 4. Comparison between the effective masses and heights according to EN 1998-4, EN 14015 and API 650

	effective impulsive mass			effective convective mass			impulsive height		convective height	
Code	**N 1998-4**	**EN 14015**	**API 650**	**EN 1998-4**	**EN 14015**	**API 650**	**EN 1998-4**	**EN 14015**	**EN 1998-4**	**EN 14015**
H/R	m_i/m	T_1/T_T	W_i/W_p	m_c/m	T_2/T_T	W_c/W_p	h_i/H	H_1/H_T	h_c/H	H_2/H_T
3,00	0,842	0,746	0,855	0,158	0,160	0,153	0,453	0,430	0,825	0,820
2,00	0,763	0,790	0,782	0,237	0,230	0,230	0,448	0,400	0,751	0,840
1,00	0,548	0,555	0,577	0,452	0,430	0,437	0,419	0,370	0,616	0,610
0,50	0,300	0,280	0,289	0,700	0,660	0,667	0,400	0,370	0,543	0,560
0,30	0,176	0,180	0,175	0,824	0,760	0,767	0,400	0,370	0,521	0,510

5.4. Design Methods

The system of Eurocodes prefers the limit states design approach, while EN 14015, API 650 and API 620 use allowable stress design methods (ASD).

EN 1998-4 distinguishes ultimate limit state (ULS) concerning structural failure and damage limitation state (DLS) ensuring the preservation of the "integrity" and "minimum operating level" of the facility [1].

EN 14015 makes a differentiation between operating basis earthquake (OBE) condition and a safe shutdown earthquake (SSE) condition that could be compared respectively to the ULS and DLS states defined in EN 1998-4.

In Section L.4 Special Provisions for Tanks Requiring Performance Level Designs, API 620 addresses even further differentiation – an operating level earthquake (OLE), a contingency level earthquake (CLE) and an aftershock level earthquake (ALE) when required by regulations or the Purchaser.

Annex E of API 650 states that the fundamental purpose of the standard is protection of life through prevention of catastrophic collapse of the tank. It does not exclude, however, damage to the tank or related components during an earthquake.

5.5. Design Impulsive and Convective Pressure and Pressure Resultants

EN 1998-4 Annex A gives a proposal for simplified method for obtaining the design pressures and pressure resultants caused by seismic action in vertical cylindrical or prismatic steel tanks, fully or partially fixed with anchors on a rigid or flexible foundation.

Formulas for the impulsive and convective pressure components are presented along with their respective horizontal resultant forces Q_i, Q_c and base moments immediately above and immediately bellow the base of the tank – respectively M_i, M_i', M_c, M_c'. All aforementioned standards provide formulas for calculation of the overturning moments and lateral (sliding) forces acting on the tank during a seismic event. API 620 gives additional provisions for calculation of the seismic pressure resultants for insulated tanks.

The idea behind the formulas provided by EN 1998-4 and API is basically the same. Nevertheless, due to differences in the design philosophy and the nature of the standards, the obtained results are different.

A comparison between the different design approaches is presented in [9]. The author studied two tanks with different parameters situated in Sliven, Bulgaria through the design methodologies prescribed by [1], [2] and [3]. He concluded that the values for T_{conv}, m_i, m_c, h_i and h_c are similar, but there are considerable differences in the values obtained for the overturning moment, sliding force and the maximum height of the wave for the first sloshing mode of the liquid contained in the tank. The most explicit differences were observed between the calculations carried out according to API 650 and EN 1998-4.

5.6. Design Checks

The design checks prescribed in EN 1998-4, EN 14015, API 620 and API 650 concern: general stability, design of tank's shell, bottom and the joint between them, anchorage and foundations.

According to EN 1998-4 in seismic design situation overturning or bearing capacity failure of the soil are not allowed. Under certain circumstances limited sliding or uplift are acceptable.

Possible tank failures are described in 3.5.2, [1]. Steel tanks are prone to certain types of failure specific only for this type of structures. One of them is "elephant foot" failure mode - buckling by vertical compression with simultaneous transverse tension. The resistance of the shell must be determined as for persistent or transient design situations [1].

While Eurocode gives only general recommendations for the main parts of the tank, EN 14015, API 650 and API 620 have a considerably larger scope of regulation. They provide requirements regarding the piping, connections, internal components, venting, floating covers, heating and/or cooling systems, stairways and walkways, ladders, earthing connections, temporary attachments and insulation.

They also provide structural requirements for thicknesses and dimensions of the different parts of the tank. API 650 even has an Annex A: Optional Design Basis for Small Tanks (normative) that provides the designer with the opportunity for certain types of tanks to avoid further calculations, choose typical sizes of tanks and obtain their capacities from a table. Also, API 650 commentary to Annex E provides Example Problems. In Eurocode such practices are not incorporated.

5.7. Complementary Measures

EN 1998-4 prescribes complementary safety measures such as bunding (the tank or tank group shall be surrounded by a ditch or an embankment). The design checks subjected to the bunding shall be more stringent than the ones for the tank itself. This is because the purpose of the enclosure is to retain its full integrity (without leakage) under the design seismic action relevant to the ULS of the tank.

5.8. Detailing

In comparison to EN 14015, API 650 and API 620, EN 1998-4 lacks provisions for detailing. In the US practice drawings and typical details with dimensions and clearances abound along with tables for direct choice of sections and sizes. The system of Eurocodes has a rather theoretical approach, while US design codes are a lot more oriented towards use in practice, facilitating the designer and saving time.

5.9. Sloshing Effect

The ground motion during an earthquake induces waves on the free surface of the liquid contained in the tank. Both European and API regulations provide formulas for calculating the height of those waves. The results obtained by following the rules in these documents, however, considerably differ from one another [9]. For such vastly used legislative documents, discrepancies like these are inadmissible.

All regulatory documents reviewed in this paper have one thing in common – none of them provides any recommendations for seismic analysis of the roof structure. API 650 EC.7.2 considers designing the roof and shell to resist sloshing wave to be impractical and does not provide such procedure. In EN 14015 the matter is discussed by a single sentence “The purchaser may specify if a freeboard is to be provided to minimize or prevent overflow and damage to the roof and upper shell“.

Both EN 1998-4 and API 650 prescribe that, unless otherwise specified, a sufficient freeboard above the maximum operating level in regard of the sloshing wave height shall be provided. Less freeboard should be sufficient if the roof is designed for the pressures caused by the wave, but no further prescriptions for that design are presented.

6. Conclusions

On the basis of the overview and comparison between the main legislative documents acting in the European Union and in the USA regarding the seismic design of steel tanks, the following conclusions can be made:

- In the territory of the European Union both EN 1998-4 and EN 14015 are in force. The symbols used in them are different and furthermore – the nature of the design approach is not the same (limit states vs. ASD). This additionally hampers the design process, especially when carried out by an engineer used to working according to the Eurocode system.

Approaching the same problems the two design codes provide different results.

All of this said, unification between the legislative documents acting in the same country is advisable. If by following the provisions of the two design codes, a proper similarity in the results is achieved, this would make them much more plausible;

- The system of Eurocodes does not give stringent requirements and procedures for seismic design of steel storage tanks. Annex A of BDS EN 1998-4 concerning seismic design of such facilities has only an informative, not a regulatory character. Also the provided procedures apply to a very narrow scope of the large variety of tanks and are valid only under certain prerequisites.

Further development of the design code is advisable. Some good practices from API could be adopted. For example detailed regulations, provision of typical details and measures and a more practical, rather than theoretical approach;

- The methodology proposed in EN 1998-4, EN 14015, API 650 and API 620 is suitable for approximate manual calculations of steel tanks by obtaining pressures and generalized forces and moments immediately below and above the joint between the cylindrical shell wall and the foundation. Analysis through computational software is not considered. With the advanced technology nowadays a rigorous analysis through a proper spatial model should not present significant difficulties and at the same time provide more realistic results;

- Apart from calculating the height of the wave excited by the seismic action, the design codes do not refer to any possible effects this wave might have on the roof of the tank. They do not provide any way to obtain the pressures caused by this wave (if the freeboard is insufficient), nor prescribe relevant design checks for the roof structure.

The main considerations are the circumferential shell, the bottom of the tank and the joint to the foundation.

Given the difference in the values for the sloshing wave height obtained by the different design codes, the opinion of the author is that the matter about roof design under a seismic situation should not be taken so lightly. Especially if the contained liquid is toxic and a possible leak could have serious consequences. Studies of the seismic behaviour of stationary roofs of steel storage tanks will be the focus of the future research work of the author.

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ПРОЕКТИРАНЕ НА СТОМАНЕНИ РЕЗЕРВОАРИ ЗА СЕИЗМИЧНО ВЪЗДЕЙСТВИЕ – ПРЕГЛЕД НА ПРЕДПИСАНИЯТА НА ДЕЙСТВАЩИТЕ НОРМАТИВНИ ДОКУМЕНТИ

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Ключови думи: *стоманен резервоар, сеизмично въздействие, Еврокод*

РЕЗЮМЕ

Сеизмичното проектиране е от първостепенно значение за всички видове конструкции, разположени в райони със средна и висока сеизмична опасност (сеизмичен хазарт). Това важи с пълна сила за стоманените резервоари, тъй като те са съоръжения с висок вторичен риск за техническата инфраструктура и/или околната среда. Резервоарите много често съдържат токсични, леснозапалими и избухливи вещества или са неразделна част от специалните обекти, свързани с отбраната, сигурността или възстановяването на страната след катастрофално събитие.

Настоящата статия представлява преглед и сравнение между действащите нормативни документи в областта на сеизмичното осигуряване на стоманени резервоари, а именно: EN 1998-4 (БДС EN 1998-4:2006, заедно с националното приложение БДС EN 1998-4:2006/NA:2012) и EN 14015 (БДС EN 14015:2005), API 650 и API 620. Фокусът е върху аспектите, които имат нужда от по-задълбочено изследване и регламентиране, както и такива, които изобщо не са засегнати в нормативната база. Специално внимание е отделено на ефектите, които би предизвикало едно сеизмично събитие, върху стационарните покриви на стоманените вертикални цилиндрични резервоари.

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