



ANALYTICAL RESEARCH OF THE BEHAVIOR OF STEEL TANKS WITH VOLUME $V=500 \text{ m}^3$ AND $V=2000 \text{ m}^3$ DURING THE SEISMIC INFLUENCE

Lyubomir A Zdravkov¹

Keywords: *Aboveground steel tank, earthquake impact, impulsive and convective parts, overturning moment, lateral shear force*

Research area: *steel structures*

SUMMARY

The vertical cylindrical steel tanks are not eternal facilities. They bear the unfavorable impacts of the environments and of the products stored in them. In order to increase the safety of their exploitation they shall be inspected at a determinate period of time and the obtained results shall be used for calculations for bearing capacity of their elements. In Bulgaria the analysis of their behavior during the seismic influence is an integral part of this type of calculation.

1. Introduction

The surveyed steel tanks (fig. 1 and 2) are situated on the area of petrol base "Sliven". Data about the name of producer, date and way of production, mounting works and date on which the facility was put into operation are missing. Technical details about the facilities are obtained from documents from its previous inspections. They are shown on the Tables 1 and 2.



Fig. 1. Steel tank – general view



Fig. 2. Vertical welding joint, made on site

¹ Lyubomir A. Zdravkov, PhD, Civil Engineer, UACEG, Sofia 1046, №1 "Hristo Smirnensky" str., floor. 7 office 733, e-mail: zdravkov_fce@uacg.bg

The last inspection gave details for verifying calculations regarding further tanks exploitation. Having in mind that the tanks are situated in a seismic area, where the coefficient of seismic acceleration $k_c = 0,15$, a part of these calculations is a check for stability during seismic influence. This verification was done according to three internationally assumed standards.

Table 1. Main technical characteristics of the tank №115 in PB "Sliven"

№	INDEX	DESCRIPTION
Main dimensions		
1.1	Nominal volume - V	$V = 500 \text{ m}^3$
1.2	Internal diameter - D	$D = 8\,580 \text{ mm}$
1.3	Height of the shell - H_s	$H = 10\,280 \text{ mm}$
1.4	Roof - type	Spherical self-supporting
Liquid (product)		
2.1	Name	kerosene
2.2	Density - ρ	850 kg/m^3
2.3	Temperature – t °C - minimal work - maximal work	min $t = - 15$ °C max $t = + 60$ °C
2.4	Overpressure - P_0^n	$P_0^n = 1,20 \text{ kPa}$
2.5	Vacuum - P_v^n	$P_v^n = 0,20 \text{ kPa}$
2.6	Maximum level of filling, according to the project	$H_t = 9\,300 \text{ mm}$
Conditions on the site		
3.1	Snow - S_n	$s_t = 1,50 \text{ kN/m}^2$
3.2	Wind - w_n	$w_m = 0,5 \text{ kN/m}^2$
3.3	Seismic zone - E	VIII – a zone, $k_c = 0,15$
3.4	Geological structure of the soil	According to the geological report
Additional data		
4.1	Material for bottom, shell and roof	ВСтЗсп according to БДС 2592-71
4.2	Construction mode	roll method

Table 2. Main technical characteristics of the tank №119 in PB "Sliven"

№	ПОКАЗАТЕЛ	ОПИСАНИЕ
Main dimensions		
1.1	Nominal volume - V	$V = 2000 \text{ m}^3$
1.2	Inside diameter - D	$D = 15\,180 \text{ mm}$
1.3	Height of the shell - H_s	$H = 11\,920 \text{ mm}$
1.4	Roof - type	Cone roof, with central column
Liquid (product)		
2.1	Name	Kerosene
2.2	Density - ρ	850 kg/m^3
2.3	Temperature – t °C - minimal work - maximal work	min $t = - 15$ °C max $t = + 60$ °C
2.4	Overpressure - P_0^n	$P_0^n = 1,20 \text{ kPa}$
2.5	Vacuum - P_v^n	$P_v^n = 0,20 \text{ kPa}$
2.6	Maximum level of filling, according to the project	$H_t = 11\,200 \text{ mm}$
Conditions on the site		
3.1	Snow - S_n	$s_t = 1,50 \text{ kN/m}^2$
3.2	Wind- w_n	$w_m = 0,5 \text{ kN/m}^2$
3.3	Seismic zone - E	VIII – a zone, $k_c = 0,15$
3.4	Geological structure of the soil	According to the geological report

Additional data		
4.1	Material for bottom, shell and roof	ВСтЗсп according to БДС 2592-71
4.2	Construction mode	roll method

2. Main damages on the tanks, caused by seismic impacts

The main damages on the aboveground steel vertical tanks caused by earthquake can be classified in the following groups [5], [6]:

- local loss of stability of the shell in the lower courses (zones of bulge and indentation). It is a result caused by the longitudinal compression forces in the shell from the tank overturning moment M_E . Often the most deformed zone in the shell is the place of horizontal welding joint, which is connecting the first two courses;
- damages in the place of joint of technological pipes with the shell. They are caused because the different stiffness of the shell and technological appliances attached to it. They can be seen in the not anchored tanks where there are serious differences of the moving of the tanks and the pipelines put into it;
- horizontal moving of the tank as a result of seismic impact;
- damages and destructions on the roof cover plates and/or construction. They are caused when there was not enough free space for waves appeared in the liquid or when the calculations of roof do not include the hydrodynamic loading of stored product;
- damages on the welding joints on the roof and on the bottom. As a result of the hydrodynamic waves the welding joint which connects bottom and roof can be destructed. In this case the stored product leaks out;
- damages or entire destruction of the anchored bolts and/ or their attachment to the roof. It is possible the extraction of the bolts from the foundation;
- damages on the stairs and platforms on the tanks.

3. Behavior of the liquid in the tank during an earthquake

The liquid's behavior during earthquake is different from the behavior of the solids. The stored into the tank liquid could be divided into two components:

- passive component – a part of the liquid near to the bottom, which moves together with the bottom and shell, such as it would be a solid. The liquid frequency is the same like the steel tank frequency. The mass of this part of the liquid is W_1 and applied point of horizontal seismic force, acting on the mass W_1 is situated at a distance X_1 from the bottom (fig. 3);
- active component – the part of the liquid near to the top, which moves freely and forms waves. This part of the liquid has its own frequency and its frequency is different from the tank's frequency. The most important is the first form of vibration. This part of the liquid has mass W_2 and applied point of horizontal seismic force, acting on the mass W_2 is situated at a distance X_2 from the bottom (fig. 3);

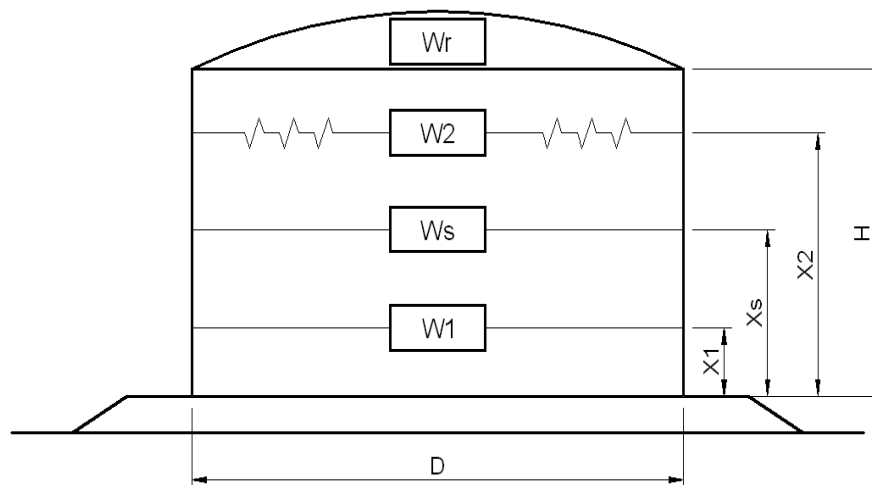


Fig. 3. Ideal tank's model of calculation of seismic impact

The two hydrodynamic components, active and passive one, cause forces which try to overturn the tank.

When the tank is not anchored and the overturning moment is strong enough, the part of the bottom can be uplift from foundation. There are cases of vertical moving of around 30 cm.

The uplifting of part of the tank is not so destructive as the damages in the places of joint of the stiff connected pipelines in the shell.

4. Calculations of the two types of steel tank for seismic impact

4.1 Calculations according to EN 14015:2004 [3]

a) uplifting of the tank and overturning moment M_E

Tank's overturning moment M_E caused by the seismic acceleration of the earth and applied at the tank's bottom, is calculated according to the formula as follow:

$$M_E = \frac{k_{c,1} \cdot (W_s \cdot X_s + W_r \cdot H + W_1 \cdot X_1) + k_{c,2} \cdot W_2 \cdot X_2}{102}, \quad (1)$$

where:

M_E is a overturning moment, applied to the level of joint between bottom and shell, kN.m;

$k_{c,1}$ – coefficient of horizontal acceleration by Earthquake. It is calculated according to [1];

W_s – shell tank's weight (fig. 3);

X_s – distance between the bottom and shell's center of gravity ;

W_r – weight of the fixed tank's roof together with the related snow upon the roof, kg (fig. 3);

H – shell height, m ;

W_1 – weight of the effective mass of the stored product which moves with shell (passive component of the liquid);

W_2 – effective mass of the stored product which moves with first form of waves forming (active component).

When $D/H_t \geq 1,333$, value for W_1 shall be calculated according to the formula:

$$W_1 = \frac{\tanh\left(0,866 \cdot \frac{D}{H_t}\right)}{0,866 \cdot \frac{D}{H_t}} \cdot W_T \quad (2)$$

When $D/H_t < 1,333$, value for W_1 shall be calculated according to the formula:

$$W_1 = \left[1,0 - 0,218 \cdot \frac{D}{H_t}\right] \cdot W_T \quad (3)$$

$$W_2 = 0,23 \cdot \frac{D}{H_t} \cdot \tanh\left(\frac{3,67 \cdot H_t}{D}\right) \cdot W_T \quad (4)$$

where W_T is the entire weight of the liquid, stored in the tank, expressed by:

$$W_T = \frac{\pi \cdot D^2}{4} \cdot H_t \cdot \rho \quad (5)$$

X_1 – distance between the place of joint of the shell to the bottom and applied point of the horizontal seismic force operating on the W_1 (fig. 3);

X_2 – distance between the place of joint of the shell to the bottom and applied point of the horizontal seismic force operating on the W_2 , m ;

The heights of the X_1 and X_2 from the place of joint of the shell to the bottom and applied point of the horizontal seismic forces operating on the W_1 and W_2 , shall be calculated according to fig. 4.

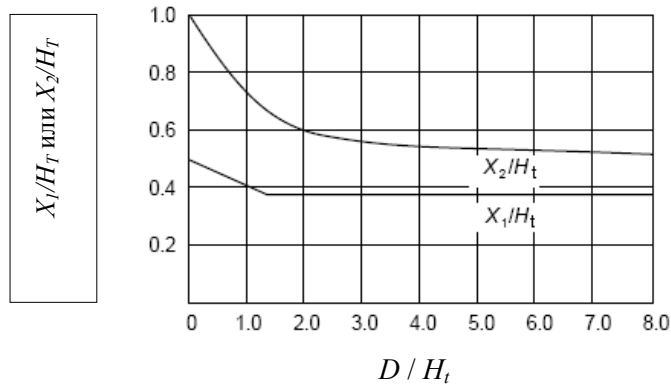


Fig. 4. Height X_1 and X_2

$k_{c,2}$ – coefficient of horizontal acceleration of earthquake. It is a function from the frequency of the liquid T_S in the first form and type of the soil under the tank.

When $T_S \leq 4,5$ s:

$$k_{c,2} = \frac{1,25 \cdot k_{c,1} \cdot S}{T_S} \quad (6)$$

where:

S is a coefficient, determined to the [Table 3](#) according to the type of the soil under the tank.

Table 3. Coefficient of the soil S

Type of the soil	Description	Coefficient S
S_1	The soil under the tank match one of the following conditions: - rock materials with the velocity of the waves $v > 760$ m/s; - solid or well tightened soil from sand, gravel or stiff clay where the soil thickness is less than 60,0 m.	1,0
S_2	solid or well tightened soil from sand, gravel or stiff clay where the soil thickness is more 60,0 m depth	1,2
S_3	There is in the soil under the tank soft or medium soft clay or sand with the thickness 6,0 ÷ 12,0 m	1,5
S_4	There is in the soil under the tank a layer soft clay with thickness more than 12,0 m	2,0

Convective component frequency of the liquid T_S in first mode shall be calculated according to the formula:

$$T_S = 1,8 \cdot k_s \cdot \sqrt{D}, \quad (7)$$

where:

k_s is a coefficient which shall be calculated according to the formula:

$$k_s = \frac{0,578}{\sqrt{\tanh\left(\frac{3,68 \cdot H_t}{D}\right)}}, \quad (8)$$

where:

D is a diameter of the tank, m ;

H_t – maximum liquid level according to the project, m.

b) horizontal (sliding) force H_E , operating on the level of joint bottom – shell

It is calculated according to the expression:

$$H_E = \frac{k_{c,1} \cdot (W_s \cdot X_s + W_r \cdot H + W_1 \cdot X_1) + k_{c,2} \cdot W_2 \cdot X_2}{102} \quad (9)$$

4.2 Calculations according to API 650, 11th Edition, 2007 [2]

a) uplifting of the tank and overturning moment M_E

The tank's overturning moment M_{rw} resulted by the seismic acceleration of the earth and applied to the tank's bottom is calculated according to the formula:

$$M_{rw} = \sqrt{[A_i \cdot (W_i \cdot X_i + W_s \cdot X_s + W_r \cdot X_r)]^2 + [A_c \cdot (W_c \cdot X_c)]^2}, \quad (10)$$

where:

W_i is the weight of the effective mass of the stored product which moves together with the shell (passive component of the liquid), [N]. It shall be calculated according to the formula (2);

W_c – effective mass of the stored product which moves with the first form of the wave forming of the liquid (active liquid component), [N]. It shall be calculated according to the formula (3).

When $D/H_t \geq 1,333$, the distance X_i between the spot of joint of the bottom and the shell and the applied point of the horizontal seismic force, operating on the W_i , m, shall be calculated according to the formula:

$$X_i = 0,375 \cdot H_t \quad (11)$$

When $D/H_t < 1,333$, distance X_i shall be calculated with the expression:

$$X_i = \left[0,5 - 0,094 \cdot \frac{D}{H_t} \right] \cdot H_t \quad (12)$$

Distance between the joint of the shell and the bottom, and applied point of force of horizontal seismic force operating on the W_c , m:

$$X_c = \left[1,0 - \frac{\cosh\left(\frac{3,67 \cdot H_t}{D}\right) - 1}{\frac{3,67 \cdot H_t}{D} \cdot \sinh\left(\frac{3,67 \cdot H_t}{D}\right)} \right] \cdot H_t \quad (13)$$

Frequency of convective component of liquid T_c in first form shall be calculated to the formula (7).

Spectrum parameter A_i of the steel structure and passive component of the liquid

$$A_i = S_{DS} \cdot \left(\frac{I}{R_{wi}} \right) = 2,5 \cdot Q \cdot F_a \cdot S_0 \cdot \left(\frac{I}{R_{wi}} \right), \quad (14)$$

where:

Q is a coefficient equal to 2/3, when the forces from the earthquake are determined according to the methods of ASCE 7, which are the described in API 650, 11th edition;

$F_a = 1,5$ – coefficient, accounted from Table E - 1 of API650 for the soil type D ;

$I = 1,0$ – coefficient, depending on importance of the tank;

$R_{wi} = 3,5$ – coefficient of behavior of impulsive liquid component when the tanks are not anchored, accounted from Table E - 4 of API 650;

S_0 – value of the elastic spectrum of reactions as a correlation to the earth acceleration g , during the period $T = 0,00$ s.

$$S_0 = 0,4 \cdot S_s = 0,4 \cdot 2,5 \cdot 0,15 = 0,15 \rightarrow \text{by API650} \quad (15)$$

$$S_0 = k_c \cdot S \cdot \left(1 + \frac{T}{T_B} \right) = 0,15 \cdot 1,15 \cdot \left(1 + \frac{0}{0,20} \right) = 0,1725 \rightarrow \text{by EN 1998 - 4} \quad (16)$$

S_s – value of the elastic spectrum of behavior as a correlation to the earth acceleration g , during the small ($T = 0,2$ s) periods;

$$S_s = \beta_s \cdot k_c = 2,5 \cdot 0,15 = 0,375 \quad (17)$$

Spectrum parameter A_c of the active components of the liquid shall be calculated according to the formula:

$$A_c = K \cdot S_{D1} \cdot \left(\frac{T_L}{T_C^2} \right) \left(\frac{I}{R_{wc}} \right) = 2,5 \cdot K \cdot Q \cdot F_v \cdot S_0 \cdot \left(\frac{T_s \cdot T_L}{T_C^2} \right) \left(\frac{I}{R_{wc}} \right), \quad (18)$$

where:

$K = 1,5$ - coefficient;

F_v – coefficient, accounted from Table E - 2 of API650 for the soil type D ;

$R_{wc} = 2,0$ – coefficient of behavior for convective (active) component of the liquid when the steel tanks are not anchored, accounted from Table E - 4;

$$T_s = \frac{F_v \cdot S_1}{F_a \cdot S_s}, \quad (19)$$

where:

S_1 – value of the elastic spectrum of behavior as correlation with the earth acceleration g , during the period $T = 1,00$ s

$$S_1 = k_c \cdot S \cdot 2,5 \cdot \left(\frac{T_c}{T} \right) \rightarrow \text{по EN 1998 - 4} \quad (20)$$

b) horizontal (sliding) force H_{rw}

Horizontal force H_{rw} , caused from the seismic acceleration of earth, applied to the level of the joint bottom – shell, is determined by the expression:

$$H_{rw} = \sqrt{[A_t \cdot (W_i + W_s + W_r)]^2 + [A_c \cdot W_c]^2} \quad (21)$$

c) height δ_s of wave in first sloshing mode

The height of the wave in the first mode of sloshing shall be calculated according to the formula:

$$\delta_s = 0,5 \cdot D \cdot A_f, \quad (22)$$

where:

$$A_f = 2,5 \cdot K \cdot Q \cdot F_v \cdot S_0 \cdot I \cdot \left(\frac{T_s}{T_c} \right), \text{ when } T_c \leq 4 \text{ s} \quad (23)$$

$$A_f = 2,5 \cdot K \cdot Q \cdot F_v \cdot S_0 \cdot I \cdot \left(\frac{4 \cdot T_s}{T_c^2} \right), \text{ when } T_c > 4 \text{ s} \quad (24)$$

4.3 Calculations according to EN 1998 - 4 [4]

a) frequency of passive (impulsive) component of the liquid T_{imp} , in the first mode shall be calculated according to the formula:

$$T_{imp} = C_i \cdot \frac{\sqrt{\rho_{product} \cdot H_t}}{\sqrt{\frac{s}{R} \cdot \sqrt{E}}} \quad (25)$$

Frequency of active (convective) component of liquid T_{conv} , in the first mode is determined according to the formula:

$$T_{conv} = C_c \cdot \sqrt{R}, \quad (26)$$

where:

H_t is the distance from the bottom to the free surface of liquid (maximum level of filling) (fig.3)

R – tank shell's radius;

s – equivalent thickness of tank shell;

$E = 2,1 \cdot 10^5$ [MPa] – modulus of the steel elasticity (Young's modulus);

C_i, C_c coefficients, shown on the Table 4:

Table 4. Coefficient $C_i, C_c, m_i, m_c, h_i, h_c, h_i', h_c'$ от EN 1998-4:2006

H/R	C_i	C_c (s/m ^{1/2})	m_i/m	m_c/m	h_i/H	h_c/H	h_i'/H	h_c'/H
0,3	9,28	2,09	0,176	0,824	0,400	0,521	2,640	3,414
0,5	7,74	1,74	0,300	0,700	0,400	0,543	1,460	1,517
0,7	6,97	1,60	0,414	0,586	0,401	0,571	1,009	1,011
1,0	6,36	1,52	0,548	0,452	0,419	0,616	0,721	0,785
1,5	6,06	1,48	0,686	0,314	0,439	0,690	0,555	0,734
2,0	6,21	1,48	0,763	0,237	0,448	0,751	0,500	0,764
2,5	6,56	1,48	0,810	0,190	0,452	0,794	0,480	0,796
3,0	7,03	1,48	0,842	0,158	0,453	0,825	0,472	0,825

Mass of the stored product m shall be calculated according to the formula (5)

b) design curve of the spectrum of behavior when the curve is type **I**

$T_B = 0,20$ s is a period for the soil type **C** ;

$T_C = 0,6$ s - is a period for the soil type **C** ;

$T_D = 2,0$ s - is a period for the soil type **C** .

Reported that $0 < T_{imp} < T_B$:

$$S_d(T_{imp}) = a_g \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2,5}{q} - \frac{2}{3} \right) \right], \quad (27)$$

where:

$a_g = 1,472$ m/s², horizontal seismic acceleration according to the project;

$S = 1,15$ – coefficient for the soil when the soil is type "C";

$q = 2,0$ – coefficient of behavior of the impulsive liquid's component, when the steel tanks are not anchored;

According to the EN 1998-4:2006, Part 3.4, steel tanks shall be measured for seismic impact when the coefficient of behavior $q > 1,5$, when:

- coefficient of the behavior for the convective component of the liquid $q = 1,0$;

- tank and its foundation are designed to resist to the overturning and or slide;

- a concentration of plastic deformation in the shell, bottom or their mutual cross point is avoided (joint bottom - shell).

Considering that $T_D < T_{conv}$

$$S_d(T_{conv}) = \max \left\{ \begin{array}{l} = a_g \cdot S \frac{2,5}{q} \cdot \left[\frac{T_C \cdot T_D}{T^2} \right] \\ \geq \beta \cdot a_g = 0,2 \cdot 1,471 = 0,294 \end{array} \right\} \quad (28)$$

where:

$q = 1,0$ is a coefficient of behavior for convective component of the liquid ;

$\beta = 0,2$ – minimum value of calculating spectrum of behavior.

c) overturning moment M_{rw}

The tank's overturning moment M_{rw} from the seismic influence, applied to the bottom of the tank is calculated according to the formula:

$$M_{rw} = (m_w \cdot h_w + m_r \cdot h_r + m_i \cdot h_i) S_d(T_{imp}) + m_c \cdot h_c \cdot S_d(T_{conv}) \quad (29)$$

where:

m_w is a mass of the tank shell;

h_w – distance from the bottom to the shell's gravity center;

m_r – mass of the tank's roof (steel cover plates, structure, snow);

h_r – distance from the bottom to the tank's roof ;

d) horizontal (sliding) force

The horizontal force Q_{rw} in the bottom of the tank from earthquake shall be calculated according to the formula:

$$Q_{rw} = (m_i + m_w + m_r) \cdot S_d(T_{imp}) + m_c \cdot S_d(T_{conv}) \quad (30)$$

e) height d_{max} of wave in first sloshing mode

The height of wave in the first sloshing mode of the liquid is calculated according to the:

$$d_{max} = \frac{0,84 \cdot R \cdot S_e(T_{conv})}{g} \quad (31)$$

5. Comparison of the obtained results

The forces by Earthquake in the surveyed tanks №115 and №119 were calculated considering equal initial conditions.

On the **Table 5** and **Table 6**, in a generalized mode for comparison were shown the results, calculated according to the three above shown standards.

Table 5. Generalized results – tank №115, $V = 500 \text{ m}^3$

Стандарт	T_{imp} s	T_{conv} s	m_i t	m_c t	h_i m	h_c m	M_E , kN.m	H_E , kN	δ_s m
EN14015		3,048	365,1	96,9	3,91	6,98	4269	784,7	
API 650		3,048	365,1	96,9	3,84	7,05	2043	485,7	0,99
EN 1998-4	0,1244	3,065	356,03	101	4,18	7,11	4785	864,9	0,198

Table 6. Generalized results – tank №119, $V = 2000 \text{ m}^3$

Стандарт	T_{imp} s	T_{conv} s	m_i t	m_c t	h_i m	h_c m	M_E , kN.m	H_E , kN	δ_s m
EN14015		4,07	1211,7	532,3	4,2	7,55	11 052	2 231	
API 650		4,07	1211,7	532,3	4,2	7,58	7 600	1 630	1,288
EN 1998-4	0,156	4,08	1169,9	553,1	4,9	7,68	13 228	2 504	0,191

6. Conclusion

On the base of the data shown in **Table 5** and **Table 6**, for these particular tanks №115 and №119, the following conclusion can be deduced:

a) too close values of frequency of convective components of the liquid T_{conv} in the first mode for all types of tanks;

b) close values for m_i , m_c , h_i and h_c , for all types of tanks;

c) serious differences in the calculated results for M_E and H_E , especially between standards API Std. 650 and EN 1998-4;

d) considerable differences in the determinations of maximum height's of waves in first sloshing mode of liquid;

e) the essential factor which creates the considerable differences between API 650 and EN 1998-4 is coefficient of behavior. According to Dr. Praveen K. Malhotra, which methodology is on the base of EN 1998-4 in the part for tanks, in general, reasons for different values of behavior coefficients are two:

- different philosophy used for design of steel tank's elements. In the API 650 - according to allowable stress design, in the EN 1998-4 on the base EN 1993-4-2 – by limit states design;

- subjective nature of coefficients of behavior. They are note based on the strong research, but on the relevant legislation which is not one and the same everywhere.

Literature:

1. НАРЕДБА №2 за проектиране на сгради и съоръжения в земетръсни райони, ДВ, бр. 68 от 2007 г
2. API Std 650, Welded Steel Tanks for Oil Storage, Eleventh Edition, June 2007.
3. EN 14015:2004, 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, November 2004.
4. Eurocode 8 – Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines.
5. HINER Larry, Soules J. G., Cooperman Alex, An Overview of Seismic Analysis of Large Storage Tanks, Chicago Bridge & Iron Company, 1999.
6. MANOS George, Evaluation of the Earthquake Performance of Anchored Wine Tanks During the San Juan, Argentina, 1977 Earthquake, Earthquake Engineering and Structural Dynamics, Vol. 20, 1991.