CALCULATION OF THE BUOYANCY OF EXTERNAL SINGLE DECK FLOATING ROOFS

Lyubomir Zdravkov[1]

University of Architecture, Civil Engineering and Geodesy

***Abstract**: Floating roofs remain the most used method of reducing losses when storing volatile petroleum products. This is due to the fact that they float on the liquid and are in continuous contact with it, which eliminates the presence of a free surface through which the product can evaporate. In the standards for design of vertical steel cylindrical tanks API Std 650, BS 2654:1989, EN 14015:2004 are written only the conditions under which floating roofs should not sink. Unfortunately, there are no instructions in them how to design the floating roofs to meet the specified requirements. Obviously, each designer is left to survive alone. During his work as a designer of steel vertical tanks, the author came across an analytical methodology for checking the buoyancy of single-deck roofs. It has been applied and tested on a significant number of tanks in Europe, Asia and Africa. Despite the trouble-free operation of the roofs, the author wishes to verify the validity of the results, obtained by analytical methods.*

***Key words**: single-deck floating roof, pontoon, membrane, buoyancy, stresses, Roark*

1. Introduction

Floating roofs are the most common method of reducing losses when storing highly volatile petroleum products. This is due to that they float on the liquid, are in continuous contact with it, which eliminates the presence of a free surface through which the product can evaporate. The company that first invented, built and place them into operation long time ago, in 1923, was "*Chicago Bridge & Iron*".

Over the years, the construction of floating roofs has developed and diversified. Now in operation are single-deck and double-deck floating roofs. The first has variations – with a "clean" membrane, with a central pontoon in the middle, with many additional floats on the membrane. The most popular type of floating roof in tanks with diameters in the range $10 \leq D \leq 60$ m is the single-deck floating roof. Its main elements are shown in fig. 1.

---

[1] Lyubomir Zdravkov, Assoc. Prof. Dr. Eng., Dept. "Steel, Timber and Plastic Structures", UACEG, 1 H. Smirnenski Blvd., Sofia 1046, e-mail: zdravkov_fce@uacg.bg

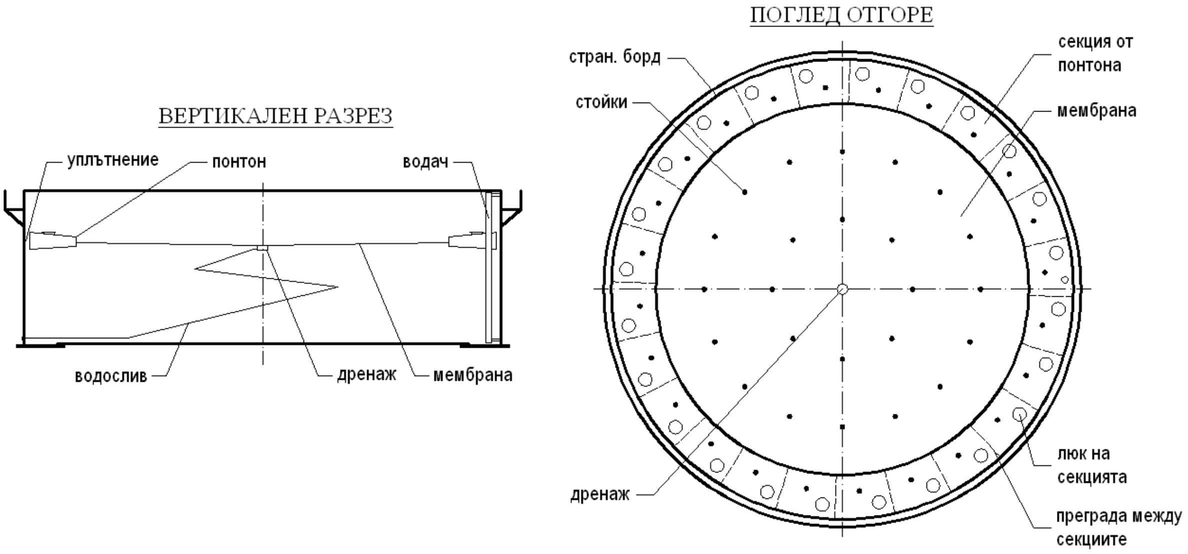


Figure 1. Single-deck floating roof with a rim pontoon

The advantages of single-deck roofs are:

a) they have a sufficiently simple and time-tested design that is easy to manufacture and mounting;

b) have a low consumption of metal per unit of covered area;

c) do not require additional mounting devices.

The disadvantages of single-deck floating roofs are mainly related to the increased deformability of the membrane, which leads to:

a) difficulties in mounting the membrane without protrusions and depressions on it, with a slope towards the drainage, located in the middle;

b) single fillet welds in the membrane are prone to fatigue failure.

In the standards for design of vertical steel cylindrical tanks API Std 650 [1], BS 2654:1989 [2], EN 14015:2004 [3] are written the following design conditions under which floating roofs must not sink:

a) 250 mm rainfall in a 24-hour period, with blocked/damaged drainage and unable to discharge the water, falling on the roof;

b) two adjacent pontoons and the membrane were punctured at the same time.

In the European standard EN 1993-4-2:2007 [4] no exist requirements for the buoyancy of roofs, because the floating roofs are not considered at all. Both in the current and the future editions of the standard.

Instructions on how to design floating roofs to meet the specified in the standards [1-3] requirements are not written in them. Obviously, each designer is left to survive alone. As a result, calculation and construction methods for floating roof are the result of internal company development and scientific research. This frequently leads to a reluctance to share them with a wider circle of designers, which is why they remain relatively unknown.

In the available literature on the field, *Lapshin et al.* [5], *Lessig et al.* [6], describe only the floating roofs, without announcing guidelines for their design. In *Myers* [7] is noticed a gradation – in addition to the types of floating roofs and their elements are shown the main requirements of API Std 650 [1]. The books of *Karavaychenko et al.* [8], *Long and Garner* [9] are the only ones in whom the author has been able to find analytical methods for verifying the sufficiency of roof buoyancy. In the article by *El-Samanody and Noaman* [10] is discussed the possibility of linear and non-linear numerical research of single-deck floating roofs.

During his work as a designer of steel vertical tanks, the author came across an analytical methodology for checking the buoyancy of single-deck roofs. It has been applied and tested at a significant number of tanks in Europe, Asia, Africa. Despite the problem-free operation of their roofs, the author wishes to verify the validity of the results, obtained through the analytical methodology.

2. Analytical method for design of single-deck floating roof

2.1. Check for the buoyancy of the roofs

The buoyancy of the roof should be checked under the following loading conditions:

a) symmetrical condition

Here we consider a situation in which there is rainwater on the roof with a height of 250 mm for a period of 24 h, which is equivalent to a uniformly distributed load p = 2.5 kN/m^2, coefficient of overloading γ_f = 1.0. The drainage is damaged and cannot discharge the water that has fallen onto the roof.

The buoyancy check includes the weight of the floating roof elements plus the weight of rainwater with a design height of 250 mm.

This check is carried out according to Archimedes' law, which, modified for the specific task, will have the following form:

$$(1) \qquad V.\rho_f = G_r + W,$$

where V is the volume of liquid displaced by the floating roof;

ρ_f – the density of the stored product. In standards [1-3] is written design value of the density ρ_f = 0.7 t/m^3, regardless of the actual density of the product in the tank.

W – the weight of water with height 250 mm on the roof;

G_r – the total weight of the floating roof.

From here, if the floating roof is constructed with a flat bottom, could be obtained its sinking in the liquid in a symmetrical condition:

$$(2) \qquad h_r = \frac{G_r + W}{A_r.\rho_f},$$

where h_r is the sinking of the pontoon of the floating roof;

A_r – the total area of the roof.

In case when the bottom of the pontoon is located Δh lower the membrane, see fig. 2, this additional volume of liquid, displaced by the pontoon, have to be taken into account. The sinking of the pontoon h_r will be determined by the formula:

$$(3) \qquad h_r = \frac{G_r + W - \Delta V.\rho_f}{A_r.\rho_f} + \Delta h,$$

where ΔV is the displaced volume by pontoon with height Δh, i.e. to membrane of the roof. It could be calculated by the simple expression:

(4) $$\Delta V = \frac{\pi\left(D_p - D_m\right)^2}{4}\Delta h,$$

where D_p is the external diameter of the pontoon, see fig. 2;

D_m – the diameter of the membrane.

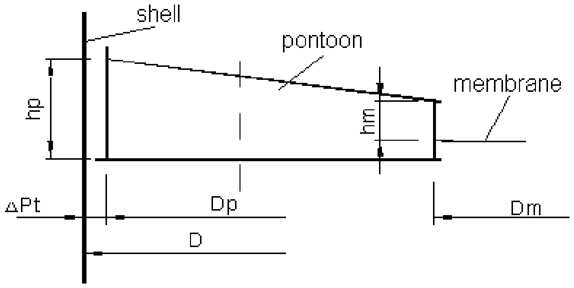


Figure 2. Section of the pontoon

b) by asymmetric condition of loading by product on the roof:

Here is considered a condition where two adjacent pontoons and the membrane are punctured at the same time. As a result, a product will penetrate into the punctured pontoons and on the membrane and the Archimedean force does not act on these elements. The buoyancy of the roof will be ensured by the rest of unpunctured pontoons only.

From Archimedes' law, we have only one equilibrium condition ($\Sigma V = 0$). Here the water uplift will be equal to the external load. The displaced by the pontoon liquid volume V_p will be:

(5) $$V_p = \frac{G_r}{\rho_f}.$$

The average sinking of the pontoon $h_{r,m}$ could be calculated as follow:

(6) $$h_{r,m} = \frac{h_1 + h_2}{2} = \frac{4V_p}{\pi\left(D_p - D_m\right)^2}\cdot\frac{n_c}{n_c - n_p},$$

where h_1 is the sinking of the pontoon from the side of the punctured compartments;

h_2 – the sinking of the pontoon from the opposite side, see fig. 3;

n_c – the number of the compartments in the pontoon;

$n_p = 2$ – the number of punctured compartments.

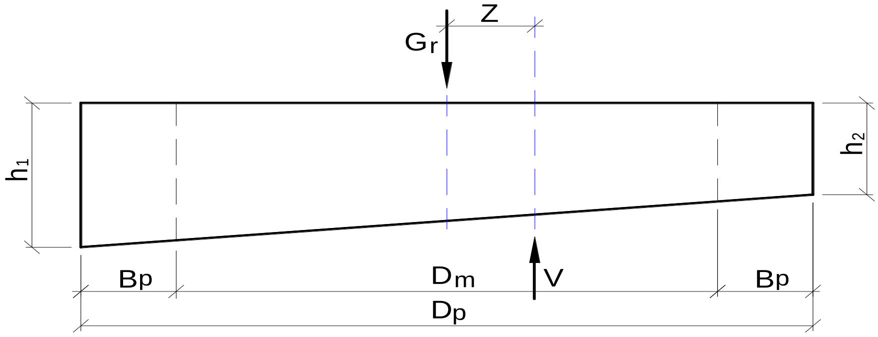


Figure 3. Asymmetrical sinking of the roof

The second equation in the system comes from the condition that the roof should be in equilibrium. The moment of rotation to the primary axis of the roof due to the self-weight of the structure will be:

$$M_G = G_r Z \,, \tag{7}$$

where Z is the distance between principal axes of the pontoon with unpunctured compartments and pontoon with two punctured compartments, see fig. 3.

Sinking of the pontoon due its rotation will be as follows:

- from the side of the punctured compartments:

$$d_1 = \frac{G_r Z}{I_{zz}} \frac{\left(\frac{D_p}{2} + Z\right)}{\rho_f} \tag{8}$$

- from the side of the sound compartments:

$$d_2 = \frac{G_r Z}{I_{zz}} \frac{\left(\frac{D_p}{2} - Z\right)}{\rho_f} \,, \tag{9}$$

where I_{zz} is the moment of inertia of pontoon with two punctured compartments.

Total sinking of the pontoon will be:

- from the side of the punctured compartments:

$$h_1 = h_{r,m} + d_1 \tag{10}$$

- from the side of the sound compartments:

$$h_2 = h_{r,m} - d_2 \tag{11}$$

The angle α of vertical rotation of the roof, see fig. 4, could be calculated by formula:

$$\alpha = \mathrm{arctg}\left(\frac{d_1 - d_2}{D_p}\right) \tag{12}$$

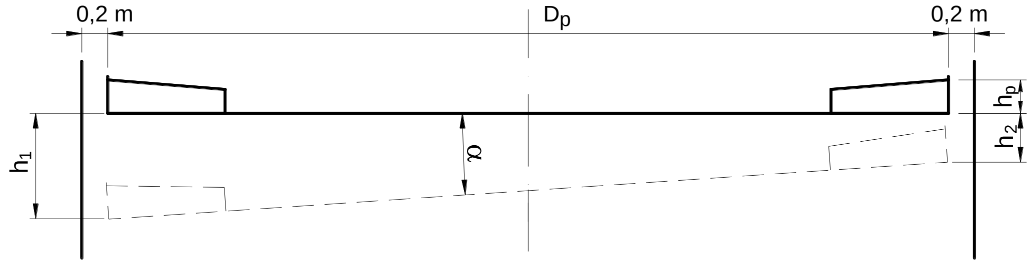


Figure 4. Vertical rotation of the roof

2.2. Determining the deformations and stresses in the membrane

Analytically, the deformations and stresses in the membrane of single-deck floating roofs can be determined by *Roark's* formulas [11]:

$$\frac{q \cdot a^4}{E \cdot t^4} = K_1 \frac{y}{t} + K_2 \left(\frac{y}{t} \right)^3 \tag{13}$$

$$\frac{\sigma \cdot a^2}{E \cdot t^2} = K_3 \frac{y}{t} + K_4 \left(\frac{y}{t} \right)^2 , \tag{14}$$

where q is the difference between the load from above, on the membrane, and the Archimedean force, acting from bellow up the membrane;

$a = D_m/2$ – the radius of the membrane of floating roof;

E – Young modulus of the steel;

t – the thickness of the sheets in the membrane;

σ – the normal stresses in the membrane;

y – the vertical deformation of the membrane in its middle, due to difference in loads q;

K_1, K_2, K_3 and K_4 – coefficients, depending on the support conditions of the membrane at its periphery.

3. A numerical method for design of single-deck floating roof

For the purposes of the present research, the steel shell structures of two single-deck roofs were modelled by commercial software ANSYS [12]. They have dimensions as follow:

a) floating roof of the tank with capacity V = 1,200 m^3

- diameter of the shell of the tank – D = 12,387 mm;
- external diameter of the pontoon – D_p = 11,980 mm;
- internal diameter of the pontoon (diameter of the membrane) – D_m = 8,300 mm;
- height of the external rim of the pontoon – h_p = 920 mm;
- distance between the bottom of pontoon and the membrane – Δh = 160 mm;
- thickness of the membrane – t_m = 5 mm;
- number of the compartments in the pontoon – n_o = 14 pcs.

b) floating roof of the tank with capacity V = 32,000 m^3, see fig. 5

- diameter of the shell of the tank – D = 42,728 mm;
- external diameter of the pontoon – D_p = 42,328 mm;
- internal diameter of the pontoon (diameter of membrane) – D_m = 36,328 mm;
- height of the external rim of the pontoon – h_p = 870 mm;
- distance between the bottom of pontoon and the membrane – Δh = 140 mm;
- thickness of the membrane – t_m = 5 mm;
- number of the compartments in the pontoon – n_o = 26 pcs.

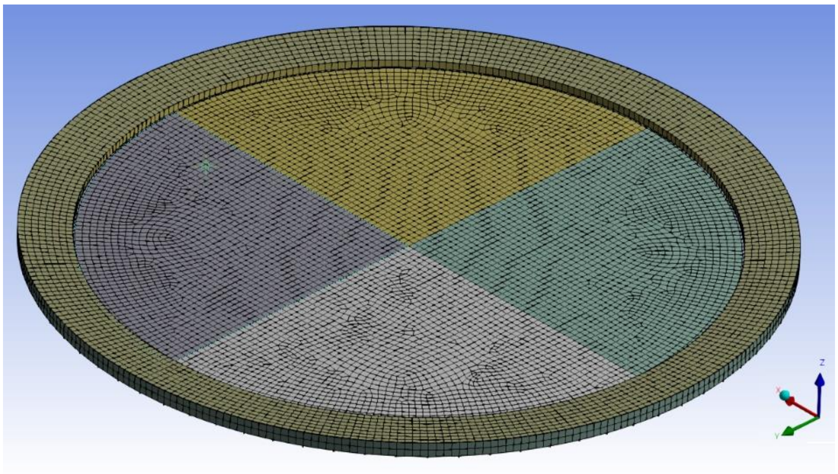


Figure 5. Numerical model of the floating roof

c) the 2D element shell181 was used to model the shell elements of the floating roofs. The method for its creation is "Quadrilateral Dominant". The finite elements are quadrangular, with four nodes at the edges. The maximum size of the elements is 200 mm for the tank with volume V = 1,200 m^3 and 400 mm for the tank with volume V = 32,000 m^3;

d) steel S235 is used in the models of floating roofs. Its mechanical properties are according to the standard EN 10025-2:2004 [13]:

- yield strength – f_y = 235 MPa;
- Young modulus – E = 210,000 MPa;
- *Poisson* ratio – ν = 0,3.

e) the material nonlinearity of steel S235 is not considered, i.e. relation stress-strain (σ-ε) is linear;

f) the sheets on lower surface of the unpunctured pontoons and membrane are elastically supported. The stiffness C changes linearly, according to the expression:

$$C = \rho_f h, \tag{15}$$

where h is the depth of sinking of the element.

g) in the research is considered the nonlinear effects of large vertical displacements and deformations (GNA) in the roof elements.

4. Results

The research was carried out in the conditions described above - symmetrical (inoperative drainage), asymmetrical (punctured two adjacent pontoons and a membrane). Another one has been added to them - normal operating conditions. With it, the roof is strong and tight, there is no water, people or snow on it. The results of the conducted analytical and numerical study are presented in detail below.

4.1. Normal operating conditions

Table 1. Sinking and stresses in the roof of tank with a V = 1 200 m^3 capacity in normal operating conditions

Type of the research	Sinking, mm			Normal stresses in the membrane, MPa	
	of pontoon	in the middle of membrane			
		by check for buoyancy	by *Roark's* formulas	in the middle	in the connection with pontoon
analytical	321	161	131	16.35	27.74
numerical	300	122		2.85	12.58

Table 2. Sinking and stresses in the roof of tank with a V = 32 000 m^3 capacity in normal operating conditions

Type of the research	Sinking, mm			Normal stresses in the membrane, MPa	
	of pontoon	in the middle of membrane			
		by check for buoyancy	by *Roark's* formulas	in the middle	in the connection with pontoon
analytical	239	99	85	0	0
numerical	304.6	80.3		4.38	47.02

4.2. Inoperative drainage and 250 mm water on the membrane

Table 3. Sinking and stresses in the roof of tank with a V = 1 200 m^3 capacity when the drainage is inoperative and 250 mm water on the membrane

Type of the research	Sinking, mm			Normal stresses in the membrane, MPa	
	of pontoon	in the middle of membrane			
		by check for buoyancy	by *Roark's* formulas	in the middle	in the connection with pontoon
analytical	493	333	378	33.03	56.98
numerical	465.7	356.1		12.72	84.28

Table 4. Sinking and stresses in the roof of tank with a V = 32 000 m^3 capacity when the drainage is inoperative and 250 mm water on the membrane

Type of the research	Sinking, mm			Normal stresses in the membrane, MPa	
	of pontoon	in the middle of membrane			
		by check for buoyancy	by *Roark's* formulas	in the middle	in the connection with pontoon
analytical	502	362	633	48.1	84.66
numerical	485.8	437.4		4.94	46.02

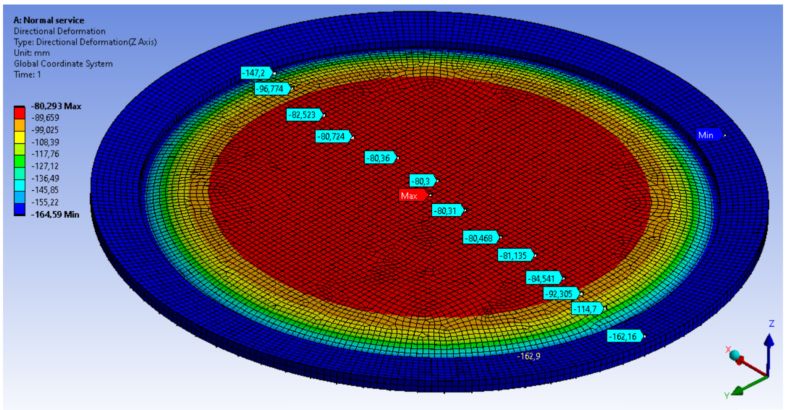
4.3. Punctured two adjacent pontoons and the membrane

Table 5. Sinking and stresses in the roof of tank with a V = 1 200 m^3 capacity in case of punctured two adjacent pontoons and the membrane

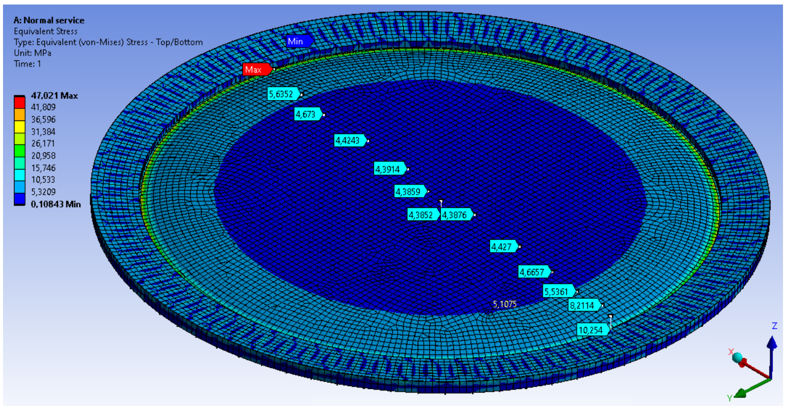
Type of the research	Sinking, mm			Normal stresses in the membrane, MPa	
	of pontoon	in the middle of membrane			
		by check for buoyancy	by *Roark's* formulas	in the middle	in the connection with pontoon
analytical	855	389	432	29.5	50.54
numerical	753	405.6		11.52	76.3

Table 6. Sinking and stresses in the roof of tank with a V = 32 000 m^3 capacity in case of punctured two adjacent pontoons and the membrane

Type of the research	Sinking, mm			Normal stresses in the membrane, MPa	
	of pontoon	in the middle of membrane			
		by check for buoyancy	by *Roark's* formulas	in the middle	in the connection with pontoon
analytical	679	421	697	49.83	87.74
numerical	532	689		31.9	107.06



a) deflection of the elements of floating roof



b) normal stresses in the elements of the floating roof

Figure 6. Results of the numerical study of a single-deck floating roof

5. Conclusions

Two single-deck floating roofs have been researched analytically and numerically. Sinking of the rim pontoon and the membrane, and the normal stresses in the middle of the membrane were checked. When comparing the results obtained by the two methods, it can definitely be stated that there are differences. According to the author, they are mainly due to the flexibility of the membrane. The conclusions reached by the author in the present study can be summarized as follows:

a) the presented there analytical methodology for determining the sinking of the pontoon and the membrane gives more considerable values compared to the numerical solution;

b) the normal stresses in the middle of the membrane, calculated by *Roark's* formulas, are greater than those obtained numerically. In the place where the membrane joins the pontoon, the situation is the opposite;

c) more accurate results are obtained through the geometrically nonlinear numerical analysis, compared to the analytical methods. Nevertheless, the last should not be thrown out of the design engineer's toolbox, as they provide an opportunity to quickly assess the decisions made.

References

[1] API Std 650, Welded Steel Tanks for Oil Storage, Thirteenth Edition. American Petroleum Institute, Washington. March 2020.
[2] BS 2654:1989, Manufacture of vertical steel welded non-refrigerated storage tanks with but – welded shells for the petroleum industry.
[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. CEN, November 2004.
[4] EN 1993-4-2:2007. Еврокод 3: Проектиране на стоманени конструкции. Част 4-2: Резервоари. БИС, януари, 2010.
[5] Лапшин А., Колесов А., Агеева, М. Конструирование и расчёт вертикальных цилиндрических резервуаров низкого давления. Учебное пособие. Нижний Новгород, ННГАСУ, 2009.
[6] Лессиг Е., Лилеев А., Соколов А. Листовые металлические конструкции. Москва, Издательство литературы по строительству, 1970.
[7] Myers P. Aboveground Storage Tanks. McGraw-Hill, 1997. ISBN 0-07-044272-X.
[8] Каравайченко М., Бабин Л., Усманов Р. Резервуары с плавающими крышами. Москва, Недра, 1992.
[9] Long, B., Garner, B. Guide to Storage Tanks & Equipment. Professional Engineering Publishing, UK, 2004.
[10] El-Samanody M., Noaman A. Design and Study of Floating Roofs for Oil Storage Tanks. Mechanics and Mechanical Engineering, vol. 21, № 1, pp. 117-136. Lodz University of Technology, 2017.
[11] Young W., Budynas R. Roark's Formulas for Stress and Strain, 7th Edition. McGraw-Hill, 2002. ISBN 0-07-072542-X.
[12] ANSYS® 2020 R2 Documentation. Ansys Inc., Canonsburg, PA, the USA.
[13] EN 10025-2:2004. Hot rolled products of structural steels - Part 2: Technical delivery conditions for non-alloy structural steels. November 2004.

To cite this article:

Zdravkov, L. Calculation of the buoyancy of external single deck floating roofs. XXIII international science conference VSU' 2023, Sofia, vol. IV, 2023. ISSN: 1314-071X