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Patterns between wall pressures and stresses with grain moisture on cylindrical silo

Hakan Kibar*

Department of Seed Science and Technology, Faculty of Agriculture and Natural Sciences, Abant Izzet Baysal University, Bolu, Turkey

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Abstract. The focus of this study were to investigate patterns between wall pressures and stresses with grain moisture of soybean and rice varieties widespread cultivated in Turkey in order to determine needed designing parameters for structure analysis in silos at filling and discharge. In this study, the wall pressures and stresses were evaluated as a function of moisture contents in the range of 8-14% and 10-14% d.b. The pressures and von Mises stresses affected as significant by the change of grain moisture content. The main cause of pressure and stress drops is changed in bulk density. Therefore is extremely important bulk density and moisture content of the product at the structural design of the silos. 4 mm wall thickness, were determined to be safe for von Mises stresses in both soybean and rice silos is smaller than 188000 kPa.

Keywords: rice; soybean; moisture content; model silo; Eurocode

1. Introduction

Steel silos are used for short and long term storage of large amount of bulks and have been built increasingly in recent years in some industries including agriculture and food processing.

The silo walls are exposed to both pressures and frictional tractions which come from the stored material inside the silo and vary all over the wall. The curve of these pressures may be symmetric or nonsymmetric and depend on whether the silo is being filled or discharged. The results of studies in this field shows that the solution of the problem of stress distributions in silos is extremely complex. However, most researchers agree that the loads acting on the silo wall are quite different pending the initial stage of filling and pending the stage of flowing in discharge.

Silo design is dominated by discharge loading conditions, which remain significantly unpredictable even in the early 21st century. The most comprehensive design standard for these loads is the new Eurocode (2007a) which defines different classes of silo by size, aspect ratio, wall roughness and construction material, as well as requiring a range of properties to be considered for the stored solids and requiring several different loading conditions to be examined in design calculations (Rotter 2009).

By contrast, storage and discharge loads in silos are complex and depend on a huge range of conditions, from the stored material and its propensity to develop cohesion, to the method of deposition, the potential for segregation, the pattern of flow of the solids, and the properties of the silo walls, as well as the geometry of the container (Rotter 2009).

Much progress has been made in the last 50 years in providing silo load guidance to design and structural engineers. Eurocode 1 is a significant advance over all previous codes, but even it does not cover many common load cases (Carson and Craig 2015). Nowadays, standards such as AS 3774, ACI 313-97 and ASAE EP433 with theoretical approaches of Janssen, Reimbert, Rankine, Airy, Forester, Caqout, Pamelard and Sor are used. Two main types of computational model are widely used to predict the responses of grains in silos: continuum models (mostly based on finite elements, FEM); and discrete models (here termed the discrete-element method, DEM) (Rotter 1998). In this context, ANSYS, ABAQUS, FELASH and other CAD finite element softwares are used (Ding *et al*. 2014, Kibar 2011, 2016). Some observers have declared that silo modelling should be abandoned in favour of finite-element models, but the latter have generally only been applied to silos as qualitative and illustrative demonstration calculations (Rotter 1998, Briassoulis 2000, Ayuga *et al*. 2005, Carson 2015, Carsaon and Craig 2015).

Following the rapid spreading of computers, the finite element, finite difference and numerical integration techniques underwent vigorous development. In particular, the finite element method is now very widely used for its flexibility. Many computer programs have been developed and effectively applied to pressure analyses. Numerical formulations for different types of analysis have been sloped: those of special interest here may be summarized as (a) linear stress analysis, (b) linear bifurcation analysis, (c) elastic large deflection analysis, (d) elastic-plastic small

*Corresponding author, Associate Professor
E-mail: hakan.kibar@ibu.edu.tr

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deflection analysis and (e) elastic-plastic large deflection analysis. Very few programs have been developed specifically for the analysis of silo structures. These were all developed to study the loads applied to silo walls by the bulk solids, and were not at all concerned with the stresses in the structure.

Unfortunately, the grains-induced loads that act on the walls and internals of such structures are not easily determined or understood. As a result, silos and bins fail with a frequency that is much higher than almost any other industrial equipment. Sometimes the failure only involves distortion or deformation which, while unsightly, does not pose a safety or operational hazard. In other cases, failure involves complete collapse of the structure with accompanying loss of use and even loss of life (Carson and Craig 2015).

The main purpose of silo wall pressure calculations is to predict silo wall stresses for structural design. The surface stresses on silo wall can be calculated directly from the external strains (Brown 2000).

The focus of this study, are now widely used for the design of the silo is made according to Eurocode (Eurocode 2007a). ANSYS 14 finite element program was used to perform of stress analysis. The main aims of this context, were investigated relationships between stress and pressure distributions in any depth on silo having a bin - hopper geometry depending on different grain moisture contents after filling and discharge.

2. Material and methods

2.1 Reference silo

The reference silo has a cylindrical bin and a conical hopper. The cylindrical bin has 20 m height and 5 m diameter. The conical hopper is 4 m height, the outlet has a diameter of 0.8 m and a hopper with an inclination of 60^0 (Fig. 1). The steel wall is assumed smooth with a thickness of 4 mm. The wall thickness was assumed constant along the height of the silo. This wall thickness, the ratio d_c/t=1250 allows the silo to be classified as a flexible wall type according to Eurocode (Eurocode 2007a). The silo wall was assumed to be made of flat steel. The silo wall was considered to be isotropic, with the mechanical properties $E=2.1\times10^8$ kPa, υ=0.3, specific weight=80 kN.m^{-3} and the design value of the yield strength=188000 kPa (Eurocode, 2001, 2007b). According to the above geometry, while storage capacity of soybean silo is 312 ton, storage capacity of rice silo is 245 ton. The reason for having different storage capacities of both soybean and rice silo are the physico and mechanical properties of grains.

2.2 Material properties

As the stored grain was considered rice and soybean. The physico and mechanical properties of rice and soybean grains were taken from Kibar and Öztürk (2008), and Kibar *et al*. (2010) are shown in Table 1. The grain moisture contents of rice and soybean grain were used as dry basis (d.b.). In silo design, physical parameters play a role, as well on the structure side as on the load side. These parameters are always subjected to some variation (Nielsen 2008).

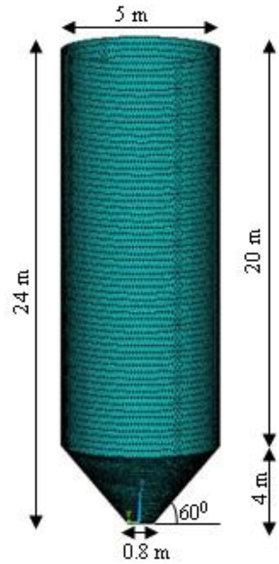


Fig. 1 Bin-hopper meshed model for the three dimensional silo

Table 1 Physico and mechanical properties of rice and soybean

Stored material	Properties	Moisture content, %			
		10	12	14	
Rice	Bulk density, kN.m^{-3}	5.955	5.799	5.605	
	Angle of internal friction, degrees	29.70	31.03	32.53	
	Grain-wall friction coefficient	0.576	0.630	0.764	
	Lateral pressure ratio	0.55	0.53	0.51	
		8	**10**	**12**	**14**
Soybean	Bulk density, kN.m^{-3}	7.660	7.490	7.370	7.260
	Angle of internal friction, degrees	27.37	28.09	29.10	30.52
	Grain-wall friction coefficient	0.164	0.183	0.219	0.248
	Lateral pressure ratio	0.59	0.58	0.56	0.54

Table 2 Classification of design situations

Action Assessment Classes (AAC)	Description
AAC 1	Silos with capacity below 100 tonnes
AAC 2	All silos covered by this Standard and not placed in another class
AAC 3	Silos with capacity in excess of 10000 tonnes Silos with capacity in excess of 10000 tonnes in which any of the following design situations occur: a) eccentric discharge with e_0/d_c>0.25 b) squat silos with top surface eccentricity with e_t/d_c>0.25

In this study used ANSYS software package to solve the stress analysis. The use of commercial software enables easier diversification of results among scientists around the world, and includes the improvements in numerical methods in a faster and more efficient manner (Vidal *et al*. 2004). The mesh used for the silo wall is shown in Fig. 1. It mainly consisted of four node shell elements (ANSYS Shell 63 element) with six degrees of freedom at each node: translations in the nodal *x*, *y*, and *z* directions and rotations about the nodal *x*, *y*, and *z* axes.

The silo design should be carried out according to the requirements of one of the following three Action Assessment Classes (AAC) used in Table 2, which produce designs with essentially equal risk in the design assessment and considering the expense and procedures necessary to reduce the risk of failure for different structures (Eurocode 2007a, Gallego *et al*. 2011) AAC 1, 2 and 3. The silo geometry in this study is Eurocode 1 AAC2.

Load cases each attain their most damaging extreme values when the stored grain properties μ, K and ϕ_{im} take characteristic values at different extremes of their statistical range, different property extremes should be considered to ensure that the design is appropriately safe for all limit states.

2.3 The pressures on the vertical walls of silo

The pressures on silo vertical walls shall be evaluated according to the slenderness of the silo, determined according to the following classes (Eurocode 2007a):
- slender silos, where $2.0 \le h_c/d_c$
- intermediate slenderness silos, where $1.0 < h_c/d_c < 2.0$
- squat silos, where $0.4 < h_c/d_c \le 1.0$
- retaining silos, where the bottom is flat and $h_c/d_c \le 0.4$

The pressures on the walls of silo hopper shall be evaluated according to the steepness of the hopper, determined according to the following classes:
- a flat bottom shall have an inclination to the horizontal α less than 5°
- a shallow hopper shall be any hopper not classified as either flat or steep.
- a steep hopper shall be any hopper that satisfies the following criterion (Eq. (1))

$$\tan\beta < \frac{1-K}{2\mu_h} \tag{1}$$

In this study, $2.0 \le h_c/d_c$ and $\tan\beta > \frac{1-K}{2\mu_h}$ is made of delicate design of the slender silo and shallow hopper.

The values of horizontal pressure (P_{hf}) and wall frictional traction (P_{wf}) at any depth after filling (Eqs. (2)-(4)) should be determined as

$$P_{hf}(z)=P_{h0}Y_J(z) \tag{2}$$

$$P_{wf}(z)=\mu\ P_{h0}Y_J(z) \tag{3}$$

$$P_{vf}(z)=\frac{P_{h0}}{K}\,Y_j(z) \tag{4}$$

in which

$$P_{h0}=\gamma\cdot K\cdot z_o \tag{5}$$

$$z_0=\frac{A}{K\cdot\mu\cdot U} \tag{6}$$

$$Y_j(z)=1-e^{-z/z_o} \tag{7}$$

The values of horizontal pressure (P_{he}) and wall frictional traction (P_{we}) at any depth after discharge (Eqs. (8), (9)) should be determined as

$$P_{he}=C_h\,P_{hf} \tag{8}$$

$$P_{we}=C_w\,P_{wf} \tag{9}$$

For slender silos in AAC2, the discharge factors should be taken as

$$C_h=1.15 \tag{10}$$

$$C_w=1.10 \tag{11}$$

The normal pressure and frictional traction at any point on the wall of a shallow hopper after filling (Eqs. (12), (13)) should be determined as

$$P_{nf} = F_f\quad P_v \tag{12}$$

$$P_{tf} = \mu_{heff}\,F_f\quad P_v \tag{13}$$

in which

$$P_v=\left(\frac{\gamma\cdot h_h}{n-1}\right)\left\{\left(\frac{x}{h_h}\right)-\left(\frac{x}{h_h}\right)^n\right\}+P_{vft}\left(\frac{x}{h_h}\right)^n \tag{14}$$

$$n=S\quad(1-b)\,\mu_{heff}\cot\beta \tag{15}$$

$$F_f=1-\left\{\frac{b}{\dfrac{1+\tan\beta}{\mu_{heff}}}\right\} \tag{16}$$

$$\mu_{heff}=\frac{1-K}{2\tan\beta} \tag{17}$$

where:
b=0.2 is an empirical coefficient
S=2 for conical and pyramidal hoppers

In shallow hoppers under discharge conditions, the normal pressure and frictional traction may be taken as identical to the values on filling.

The results obtained were subjected to analysis of stresses using ANSYS software and graph drawing using MS-Excel.

3. Results and discussion

During filling with the soybean, the variations in the horizontal pressures and wall friction traction were shown in Fig. 2. Fig. 2 shows the relationship between grain moisture content and horizontal pressures. The horizontal pressures and wall friction traction of soybean affected by the change of moisture content. This leads to the proportional change between parameters. The main cause of pressure drop was bulk density decrease. The angle of internal friction often changes with pressure, usually increasing as lower pressure. A similar result was obtained in cylindrical bin has an aspect ratio of 17.62 m height and 4.00 m diameter by Rejowski and Ivicki (2016). In their study, found that increased from the top towards the bottom of the silo of wall friction traction. The horizontal pressure values and wall friction traction in the transition zone were found to be higher than the cylinder zone. While the highest value (109.66 kPa) for the horizontal pressures were recorded at 8% grain moisture content, the lowest value (9.82 kPa) for the horizontal pressures were recorded at 14% grain moisture content. The change with silo height of pressures of bulk materials against silo wall has been reported by Kaminski and Maj (2009).

A comparison between the stresses predicted according to ANSYS and grain moisture content values were shown in Fig. 3 during filling where the most significant stresses were the von Mises stresses. von Mises stresses show a peak at hopper of load application. High stress values have generally occurred in the high ends or the low ends of the transition to the hopper in the models. The main cause of this situation stems from the weight the product filled in the silo causes upon the base. The maximum stresses obtained at 8% grain moisture content in the silo-hopper are 97002 kPa during filling of soybean.

The wall friction traction in the hopper are more complicated than in the cylindrical zone. The wall friction traction curve distribution as shown in Fig. 2. The wall friction traction of soybean was affected by the change of grain moisture content. The wall friction traction varied between 2.51 and 16.34 kPa, depending on grain moisture content. At the transition to the hopper the wall friction traction has a discontinuity caused by the sudden change of

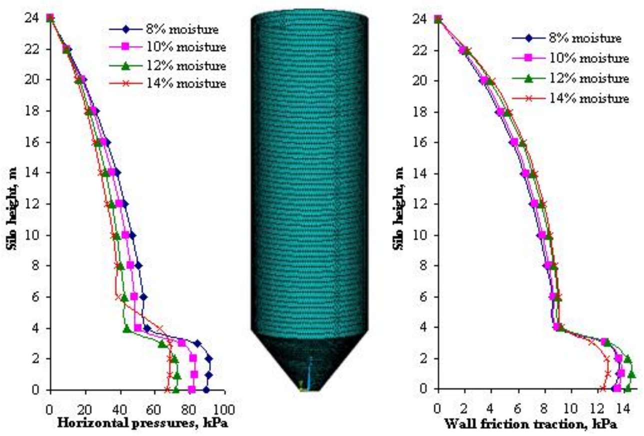
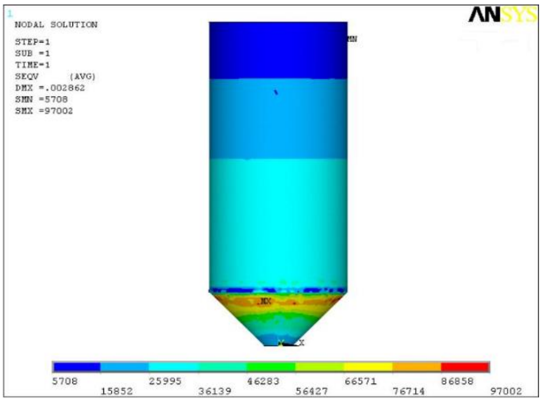


Fig. 2 Silo wall pressures during soybean filling



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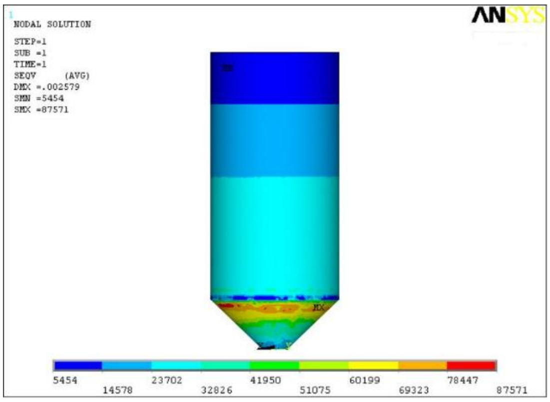

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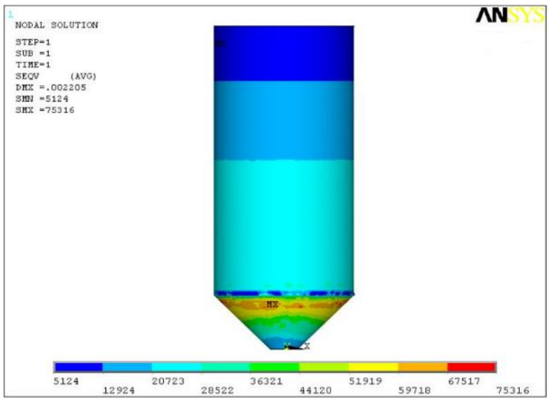

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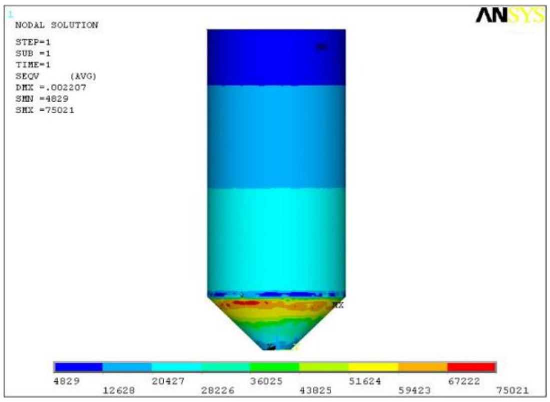

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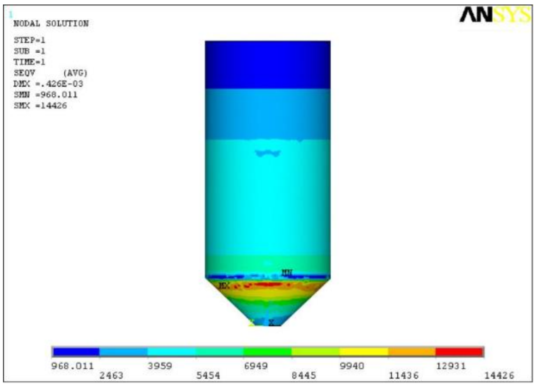
Fig. 3 The effects of the horizontal pressure on stress distribution at different moisture contents during filling of soybean



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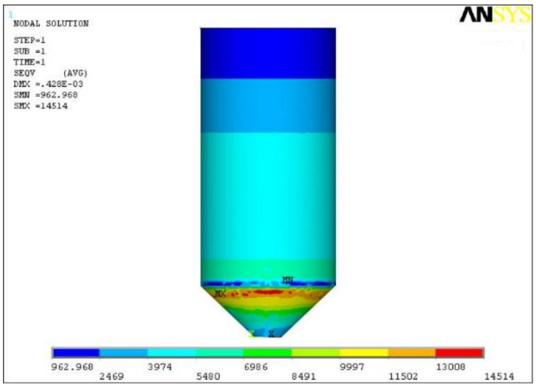

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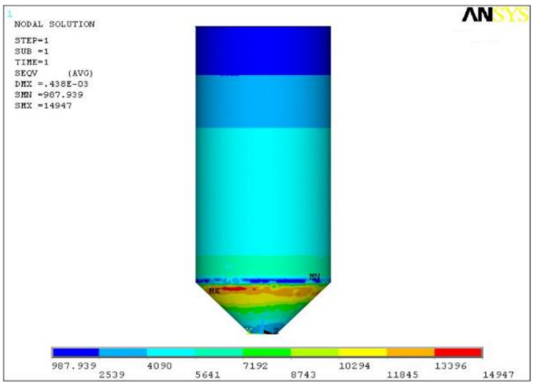

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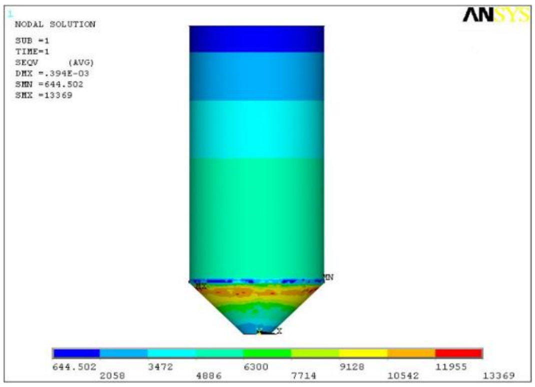

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Fig. 4 The effects of the friction traction on stress distribution wall at different moisture contents during filling of soybean

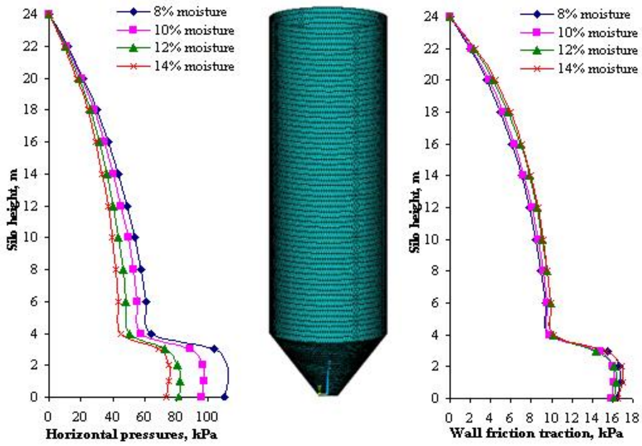


Fig. 5 Silo wall pressures during soybean discharge

wall tendency. Further downwards in the hopper both the horizontal pressures and the wall friction traction are decreasing at the hopper apex, but depending the horizontal pressures at the transition, the silo shape and the grain physical properties of the pressures in the hopper either increase in the first instance and then decrease, or decrease continuously from the transition to the apex as in Fig. 2. Similar results for different granular agro-materials have been reported by Öztürk and Kibar (2008a) for hazelnut varieties and, Öztürk *et al*. (2008b) for corn varieties. The variation with depth of the wall friction traction stresses exerted by the soybean at the end of filling was shown in Fig. 4, where it can be seen that high stresses were developed near the transition of hopper because of grain moisture content. The highest von Mises stress was obtained at 12% grain moisture content. In this grain moisture content, maximum stresses were obtained at the silo-hopper transition with values of 14947 kPa. A similar result has been reported by Link and Elwi (1987), Song (2004) and Ding *et al*. (2014).

Fig. 5 shows the distribution of horizontal pressures and friction traction curves along the silo wall at discharge during. These curves showed variations depending on the change in grain moisture content. The horizontal pressures were detected to decrease with change in grain moisture content (Fig. 5). The highest value for the horizontal pressure (109.66 kPa) was determined at grain moisture content of 8%. The lowest value for horizontal pressure (9.82 kPa) was at grain moisture content of 14%. Similar results have been reported by Öztürk and Kibar (2008a), and Öztürk *et al*. (2008b).

The predictions of the stress relationships between horizontal pressure and grain moisture content on the cylindrical and hopper wall under dicharge are shown in Fig. 6, together with the stresses from the last stage of the progressive discharge. The main stress directions were detected to be close to horizontal and vertical everywhere, with the von Mises nearly transition. The stress values close to minimum were obtained in around the outlet in that the lower of the pressure exerted by soybean, where the product output exists, again in the models. Much has been made of high local pressure, but structural research studies have shown that it is not critical to the strength of steel silos, and is indeed beneficial (Teng and Rotter 1991).

The wall friction tractions were found to change with

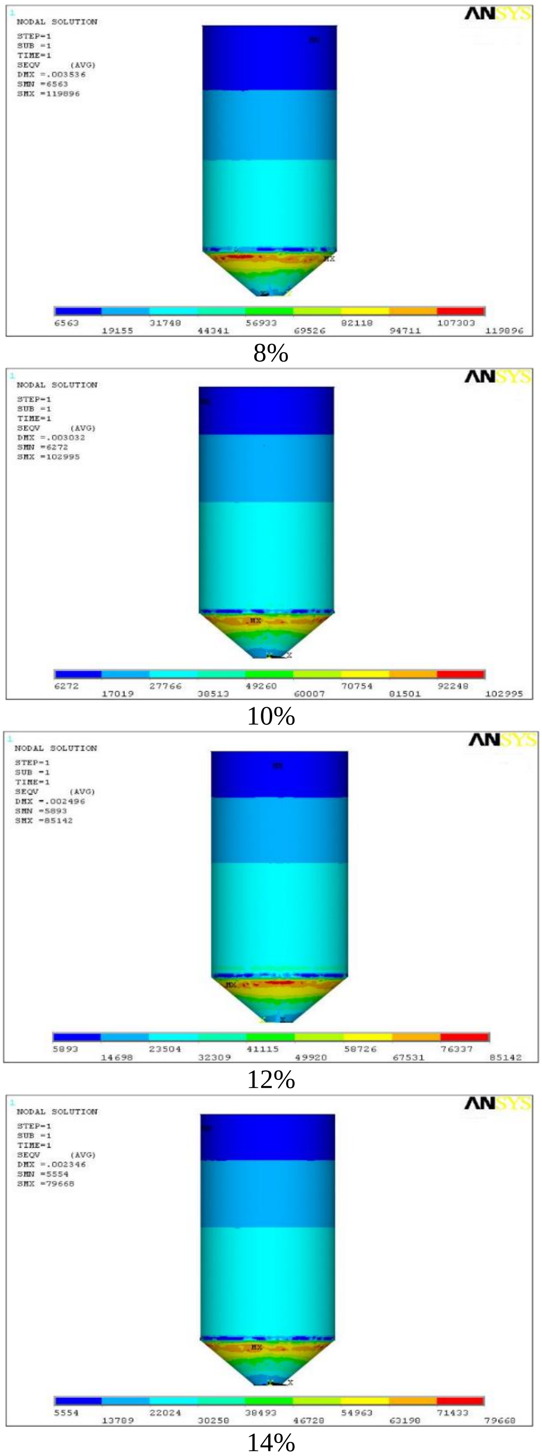


Fig. 6 The effects of the horizontal pressure on stress distribution at different moisture contents during discharge of soybean

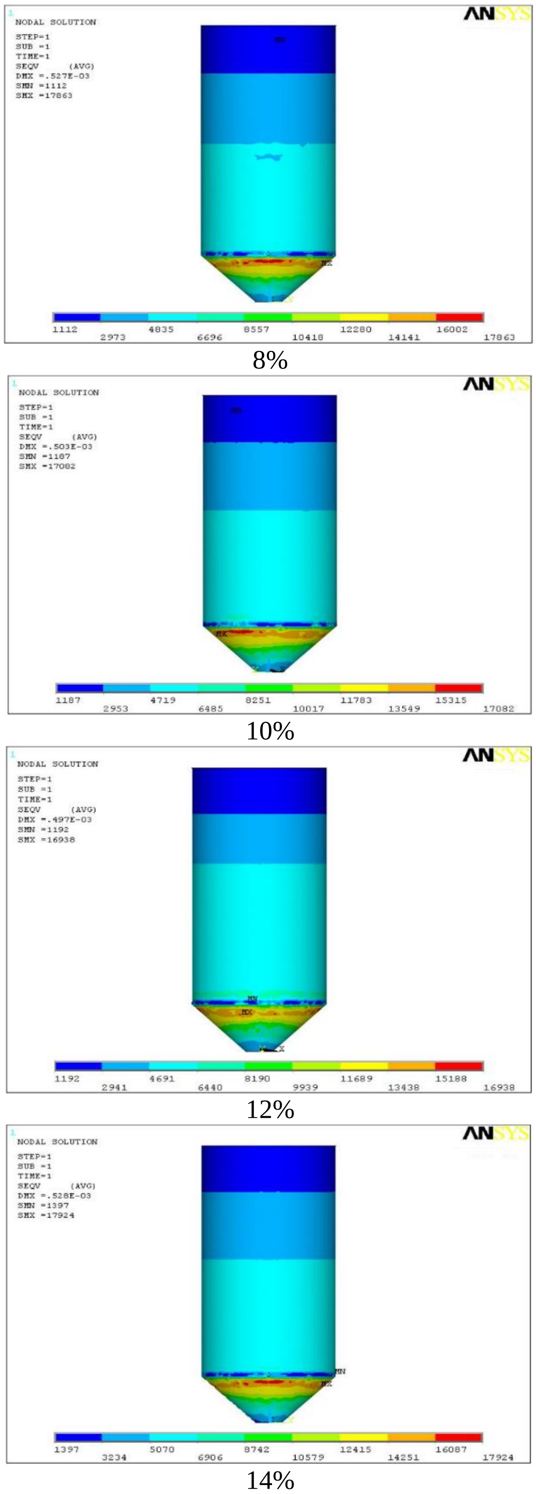


Fig. 7 The effects of the friction traction on stress distribution at different moisture contents during discharge of soybean

grain moisture content (Fig. 5). The highest value for wall friction traction was determined at grain moisture content of 14% (16.96 kPa) and the lowest value at grain moisture content of 8% (1.97 kPa). A typical development of stress at points on the silo wall surface during discharge was shown in Fig. 7. The largest von Mises stresses obtained in the silo-hopper (about 17924 kPa) at 14% grain moisture content. A similar result has been reported by Song (2004).

The results of silo pressures were presented depending on filling conditions at different grain moisture content in Fig. 8. The horizontal pressures were detected to change with the change in grain moisture content (Fig. 8). A peak pressure is obtained with 10% grain moisture content (23.95 kPa) at the silo-hopper. In the both cylindrical and hopper section of the silo it can be seen the trend of lower pressures

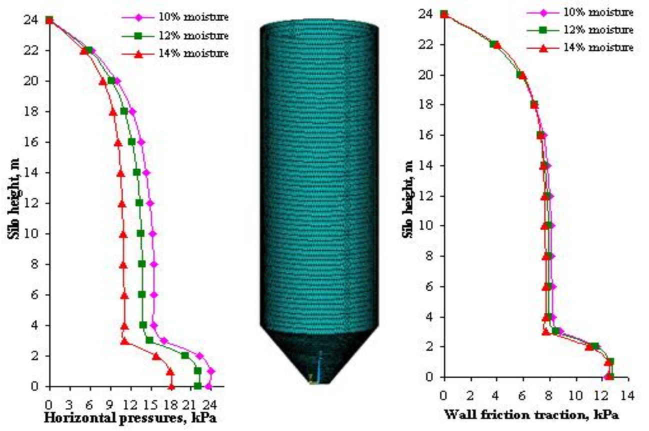


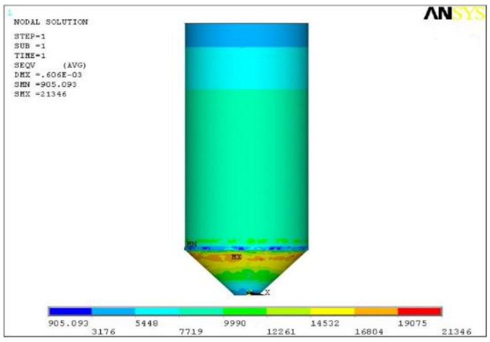
Fig. 8 Silo wall pressures during rice grain filling

as the bulk density changes. As the cause of the change, relative change in bulk density of grains can be shown to be higher than the other physico and mechanical parameters. Typical von Mises stresses in the horizontal during the filling processes were given in Fig. 9. The von Mises stresses at the mid-height of the hopper were larger than that obtained with the hopper outlet. A similar result has been reported by Brown (2000). Goodey *et al*. (2017) the highest pressure during the filling in 10 m high silo was determined in the transition zone. The results obtained are similar to this study.

Fig. 8 shows the information about the values of wall friction traction which are obtained from different heights. The wall friction tractions were found to affected by the change in grain moisture content. From Fig. 8 was evident that wall friction tractions are smaller for greater values of wall friction coefficient. The reason for this can be shown change with increase in moisture content of the horizontal pressure in equation used to calculate the wall friction traction. Also, this difference may be explained due to the value of grain moisture content. A similar result has been reported by Masson and Martinez (2002). The variation in the von Mises stresses at grain heights for 5 m diameter grain silo was shown in Fig. 10. The maximum von Mises stresses are located near the mid-height of the silo-hopper. The stresses caused by frictional traction were lower than other types of pressure. In this case, the rice parameters in Eurocode 1 equation are effective. A similar result has been reported by Link and Elwi (1987), and Song (2004).

The wall pressures in the reference silo were determined to vary with respect to grain height. The horizontal pressures and wall friction traction calculated during discharge for different grain heights were shown in Fig. 11. The minimum horizontal pressure values obtained for 14% grain moisture content in the reference silo are 5.92 kPa for discharge conditions. The maximum horizontal pressure values were 30.92 kPa obtained at 10% grain moisture content. According to the results obtained, the discharge pressures are determined higher than filling pressures. Zhu *et al*. (2012) the highest pressures during the discharge for silo in 25 m high were determined in the lower zones of the silo. The results obtained are similar to this study.

Similar results have been reported by Walker (1966),



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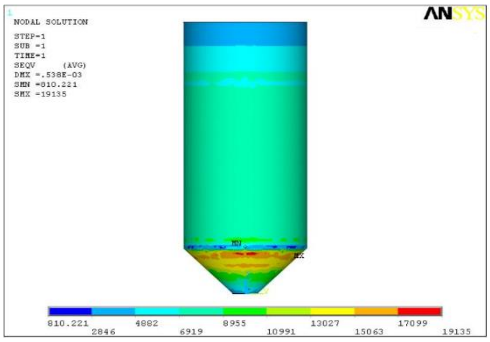

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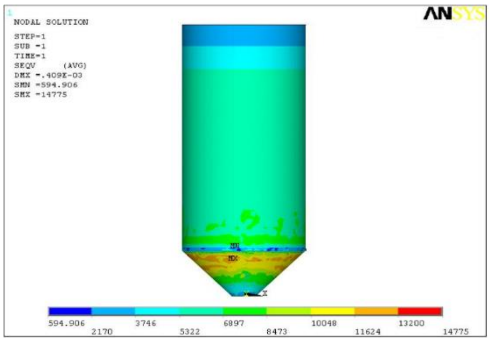

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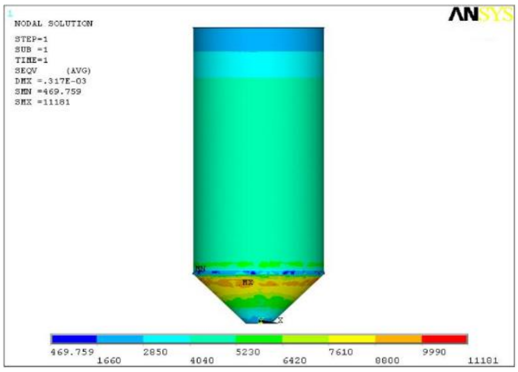
Fig. 9 The effects of the horizontal pressure on stress distribution at different moisture contents during filling of rice grain

Drescher (1991), Nedderman (1992) and Sanad (2001). Fig. 12 show the distributions of the von Mises stresses. The maximum Mises stresses are located near the mid-height of the hopper. However, significant Mises stress is also observed at the bottom of the silo.

Fig. 11 shows the wall friction traction on the silo walls for discharge conditions. A peak pressure of 16.20 kPa was obtained with 10% grain moisture content at the silo-hopper. According to ANSYS analysis, closing to the bottom part of the silo, stresses decrease after they reached the maximum value. As the reason for this, may be explained differences between values of grain moisture content, bulk density and grain-wall friction coefficient. The cylindrical wall may also be subject to frictional tractions due to the sliding of material down the wall. The very slight settlements which occur in bulk solids as they are progressively loaded into the silo are almost always sufficient to mobilize the friction fully. These loads lead to axial (vertical) compressive loads in the wall, which increase progressively down the wall. The von Mises stress



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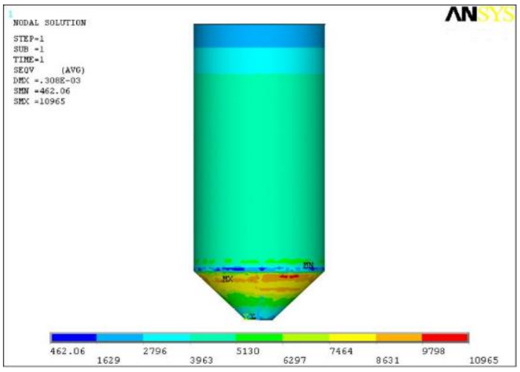

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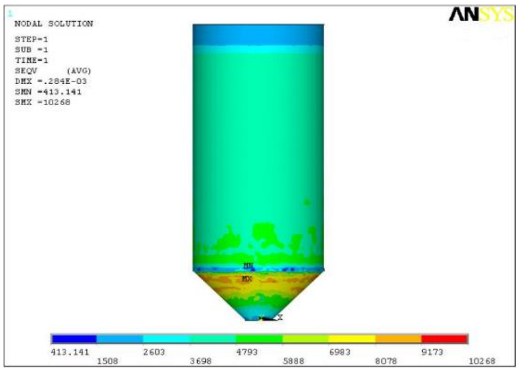

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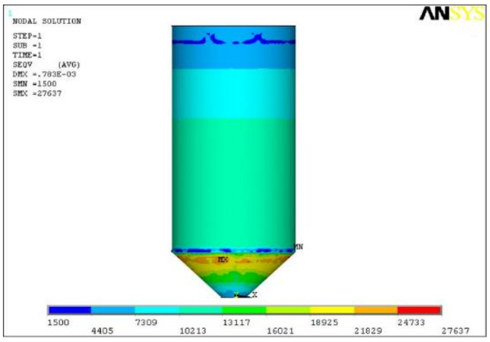
Fig. 10 The effects of the friction traction on stress distribution at different moisture contents during filling of rice grain



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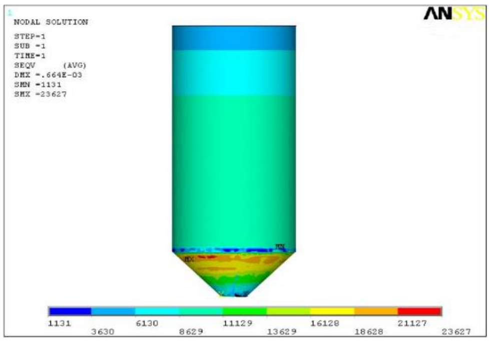

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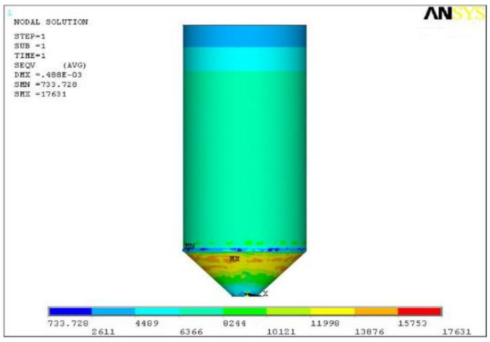

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Fig. 12 The effects of the horizontal pressure on stress distribution at different moisture contents during discharge of rice grain

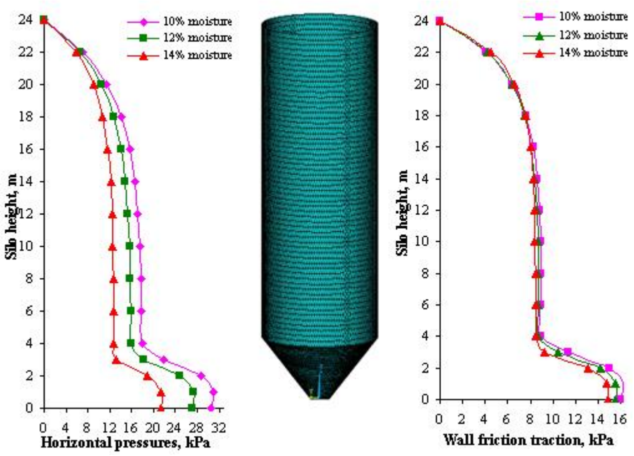

Fig. 11 Silo wall pressures during rice grain discharge

distributions were shown in Fig. 13. Fig. 13 shows that there may be high of stresses in hopper area. The maximum von Mises stresses were located near the mid-height of the silo-hopper. The finite element results showed a large sensitivity of stresses in bulk solids due to the change of the direction of shear deformation along the silo wall (Tejchman 2002).

4. Conclusions

This paper has focused a detailed investigation the effects of grain moisture content on the pressures and stresses of slenderness silos. The reference silo was shown exhibit significant informations related to strength under concentric filling and discharge depending on Eurocode and ANSYS structural assessment. The wall pressures and friction tractions were decreased both filling and discharge conditions when grain moisture content increased from 8% to 14%, and 10% to 14%, respectively. In tis study, the von

Misses stresses decreased with the increase of moisture content in grains (soybean and rice). Depending on this, necessary precautions should be taken in order not to increase the grain moisture content in silos. Because moisture content can cause changes in the pressures and stresses.

As a result, it is common for designers to oversimplify the problem, and especially to misdiagnose the cause of structural damage. A careful analysis of the pressures and stresses in different modes shows that this failure mode is only critical near the surface or in slender silos. The aspect ratio of the silo is a key determinant of pressures and stresses in filling and discharge conditions. Where silos have an internal system of discharging, only filling pressures need to be considered, so simpler safe designs are possible. Therefore, the silo wall thickness during design should be chosen depending on high stresses in cylindrical and hopper sections. Nevertheless, some adjustments would be done to adopt the ANSYS results and even experimental results better.

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