Tower silo design loads for wet silages

J.C. JOFRIET, Z. YAO and S.C. NEGI

1School of Engineering and 2Food Science Department, University of Guelph, Guelph, ON, Canada N1G 2W1. Received 3 October 1991; accepted 11 June 1992.

Jofriet, J.C., Yao, Z. and Negi, S.C. 1992. Tower silo design loads for wet silages. Can. Agric. Eng. 34:375-381. Wet silage stored in tower silos may become saturated if sufficiently consolidated. If this occurs, liquid pressures will result in the saturated silage zone. This paper briefly reviews a comprehensive study of the magnitude of liquid pressures and of the extent of the saturated silage zone. The latter is a function of silo size and of the moisture content of the silage. On the basis of the results of the recent study, recommendations are made for determining the height of the saturated zone for both silos with and without adequate drains. The recommended saturation heights are greater than those in the 1990 CFBC. It is also proposed that the CFBC wall load recommendations are suitable for silos without adequate drains. For those with drains, the wall loads could be reduced considerably in the lower part of the silo. Specific design formulae are provided.

INTRODUCTION

A direct consequence of storing wet material in a tower silo is the build-up of liquid pressure in the bottom, especially if the hydraulic conductivity of the material is low. The liquid pressure is superimposed onto the effective wall pressure (pressure transmitted through the particulate skeleton), and the total lateral pressure is usually considerably greater than for dry materials because of the relatively large magnitude of the liquid pressure.

't Hart et al. (1979) observed that liquid pressures were three times the effective pressure in a steel silo filled with corn silage. Therefore the prediction of liquid pressure is essential for silo design. If it is neglected or underestimated in a cast-in-place concrete silo, or other type with impervious walls, a collapse or serious damage may result.

There are several silo design codes in force in Europe and North America. Design standards for silos storing relatively dry material (M < 65% w.b.) are fairly well established. However, the standards for silos filled with wet silage (moisture content > 65%) vary greatly from code to code.

The Canadian Farm Building Code (NRC 1990) classifies top-unloading farm tower silos intended for wet silage as class II. In class II silos saturation is expected when:

\[ M > 80 - 0.5(H + D) \]

where:

- \( M \) = moisture content on a wet basis (%),
- \( H \) = silo height (m), and
- \( D \) = silo diameter (m).

For design, it is assumed that the silo can be filled to the top, hence silo height and filling height are considered equal. The pressure in Class II silos above the saturation level is represented by a bilinear function based on the well-known Janssen’s (1895) theory (NRC 1990). Below the saturation level the total (effective plus hydrostatic) pressure is given by:

\[ P_t = P_s + (z - z_s)(1.0 - 4\mu K D) P_s \]

where:

- \( z \) = depth from the top of silo (m),
- \( z_s \) = depth to saturated zone (m),
- \( \mu \) = friction coefficient,
- \( K \) = pressure ratio,
- \( P_t \) = pressure at depth \( z \) (kPa), and
- \( P_s \) = pressure at depth \( z_s \) (kPa).

An empirical equation:

\[ z_s = 160 - 2M - D \]

is used to calculate the depth from the top of the silo to the saturated zone.

The British Standard Institution suggests in the standard BS 5061 (BSI 1974) that the lateral pressure \( P_t \) at depth \( z \) in drained cylindrical silage tower silos is:

\[ P_t = 9.8 + 0.75(9.8 - \frac{29.5}{D}) (z - 3) \]

The factor 0.75 in the second term of Eq. 4 is changed to 1.0 if the crop is ensiled in a watertight silo.

The German Standard DIN 1055 (Deutsche Normen 1977) simply relates pressure \( P_t \) to silage depth \( z \):

\[ P_t = 4.0z \]
Equation 5 applies to a silo height of 20 m or less and silage moisture contents ranging from 60 to 77% (w.b.). The standards of the International Silo Association (ISA 1981) do not consider wet silage and the possibility of hydrostatic pressures.

The objective of this paper is to use the results of previous research related to the effect of silage saturation in tower silos (Lau and Jofriet 1988; Tang and Jofriet 1989; Yao and Jofriet 1991) to formulate design loading recommendations for tower silos that may be subjected to liquid pressures. Both drained and undrained structures will be discussed.

**BACKGROUND RESEARCH**

Tang and Jofriet (1989) and Yao and Jofriet (1991) have presented a simulation procedure for predicting numerically the lateral pressures (liquid and effective pressures) in silos filled with high moisture content material. Three time dependent processes were modelled in the simulation computer program: filling, consolidation, and drainage. Previously Lau and Jofriet (1988) had shown that excess pore pressures are insignificant in the silo filling/silage draining process.

The numerical models were verified against an experiment conducted by ‘t Hart et al. (1979) in the Netherlands. The test was carried out in a 6.19 x 18.15 m glass lined steel farm silo. The simulation was carried out for a period of 30 days. The simulated results for the total and liquid lateral pressures at 7, 14, 21, and 30 days were compared with those of ‘t Hart. Figure 1 shows the comparison at 14 days. The pressures compared well at all time steps. The settled silage height was within 0.25 m of the experimental value at 7 days and virtually equal to it at 30 days.

Subsequently, Yao and Jofriet (1991) carried out a parametric study of farm silos filled with alfalfa silage. It addressed the three most important parameters that affect wall pressures: silo height, silo diameter, and silage moisture content. Most analyses assumed adequate drainage in the bottom of the silo. A limited number of analyses were carried out with undrained silos. The results of the parametric study are relevant to silos intended for alfalfa and grass. They will be conservative for corn silage because it has a lower bulk density and drains faster (Tang and Jofriet 1989).

Four diameters ranging from 3.7 to 9.1 m were chosen. For the 3.7 m diameter, silo heights of 9.1, 12.2, and 15.2 m were investigated to represent small, medium, and large silo aspect ratios. The silo heights for the 4.9 m diameter were 15.2, 18.3, and 21.3 m and for the 6.1 m diameter 18.3, 21.3, and 24.4 m. The large diameter silos were 9.1 x 24.4 m, 9.1 x 27.4 m, and 9.1 x 33.5 m. This range of sizes covers the silo sizes used by Canadian farmers today. Moisture contents (w.b.) of 60%, 65%, 70%, and 75% were chosen for the parametric study.

The results of the 48 analyses of drained silos are shown in Table I. For each analysis, Table I presents in column 4 the maximum saturation height measured from the silo bottom, in column 6 the average bulk density, and in columns 8 and 9 the maximum liquid and total pressures on the silo wall. For comparison, the tables include the CFBC values of saturation height determined with Eq. 3 (column 5); the average bulk density suggested by the CFBC (column 7); and in column 10 the maximum pressure as per the CFBC using Eqs. 2 and 3 (column 10).

Figure 2 illustrates the maximum pressures for a 3.7 x 12.2 m silo; maximum total pressures for 65%, 70%, and 75% moisture content silage are shown. Figure 3 has the same plots for a 9.1 x 27.4 m silo.

The effect of not providing adequate drainage was determined for three silo sizes and for three moisture contents (65%, 70%, and 75% w.b.). The saturation height, the bulk density, and the maximum liquid pressures and total pressures are presented in Table II, together with corresponding values calculated from the CFBC. The CFBC values are exactly the same as those in Table I because this code does not differentiate between silos with and without adequate drains.

The effect of drainage is illustrated in Fig. 4 in which two sets of pressures are plotted for the 4.9 x 18.3 m silo filled with 70% moisture content alfalfa silage, one with and one without a drain. The simulation of the silo with the floor drains showed pressures reaching a maximum at about 4 days. The silo without drains had pressures increasing until $t = 18.8$ days.

**DISCUSSION OF SIMULATION RESULTS AND DESIGN LOAD RECOMMENDATIONS**

At a moisture content of 60%, saturation [Tang et al. (1988) saturation criterion] occurred in the simulation analysis only
### Table I. Simulated saturation heights and maximum pressures in drained silos

<table>
<thead>
<tr>
<th>H (m)</th>
<th>D (m)</th>
<th>M (%)</th>
<th>Saturation height</th>
<th>Bulk density (kg/m³)</th>
<th>Maximum pressure (kPa)</th>
<th>Saturation height</th>
<th>Maximum pressure* Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>simul CFBC</td>
<td>simul CFBC</td>
<td>Simulation liq tot</td>
<td>Eq. 2</td>
<td>Eq. 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(m)</td>
<td>CFBC</td>
<td>(m)</td>
<td>(kg/m³)</td>
<td>(m)</td>
</tr>
<tr>
<td>9.1</td>
<td>3.7</td>
<td>60</td>
<td>0.0</td>
<td>0.0</td>
<td>679</td>
<td>691</td>
<td>0</td>
</tr>
<tr>
<td>9.1</td>
<td>3.7</td>
<td>65</td>
<td>0.0</td>
<td>0.0</td>
<td>681</td>
<td>691</td>
<td>0</td>
</tr>
<tr>
<td>9.1</td>
<td>4.9</td>
<td>65</td>
<td>0.4</td>
<td>0.0</td>
<td>803</td>
<td>787</td>
<td>0</td>
</tr>
<tr>
<td>9.1</td>
<td>4.9</td>
<td>65</td>
<td>0.4</td>
<td>0.0</td>
<td>825</td>
<td>787</td>
<td>0</td>
</tr>
<tr>
<td>9.1</td>
<td>4.9</td>
<td>65</td>
<td>1.3</td>
<td>0.0</td>
<td>863</td>
<td>787</td>
<td>2</td>
</tr>
<tr>
<td>9.1</td>
<td>6.1</td>
<td>65</td>
<td>3.3</td>
<td>0.0</td>
<td>855</td>
<td>865</td>
<td>5</td>
</tr>
<tr>
<td>9.1</td>
<td>6.1</td>
<td>65</td>
<td>7.0</td>
<td>0.0</td>
<td>891</td>
<td>865</td>
<td>9</td>
</tr>
<tr>
<td>9.1</td>
<td>6.1</td>
<td>65</td>
<td>9.8</td>
<td>0.5</td>
<td>912</td>
<td>865</td>
<td>14</td>
</tr>
<tr>
<td>9.1</td>
<td>6.1</td>
<td>65</td>
<td>13.1</td>
<td>3.5</td>
<td>948</td>
<td>996</td>
<td>24</td>
</tr>
<tr>
<td>9.1</td>
<td>6.1</td>
<td>65</td>
<td>15.9</td>
<td>6.6</td>
<td>971</td>
<td>996</td>
<td>32</td>
</tr>
<tr>
<td>9.1</td>
<td>6.1</td>
<td>65</td>
<td>21.5</td>
<td>12.7</td>
<td>1007</td>
<td>996</td>
<td>43</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>70</td>
<td>0.5</td>
<td>0.0</td>
<td>818</td>
<td>840</td>
<td>0</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>5.0</td>
<td>2.8</td>
<td>1016</td>
<td>1037</td>
<td>17</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>7.5</td>
<td>5.8</td>
<td>1086</td>
<td>1037</td>
<td>29</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>11.3</td>
<td>8.9</td>
<td>1140</td>
<td>1103</td>
<td>41</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>11.3</td>
<td>10.1</td>
<td>1174</td>
<td>1156</td>
<td>43</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>14.8</td>
<td>13.2</td>
<td>1225</td>
<td>1156</td>
<td>55</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>17.5</td>
<td>16.2</td>
<td>1261</td>
<td>1156</td>
<td>61</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>14.7</td>
<td>14.4</td>
<td>1245</td>
<td>1263</td>
<td>57</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>18.0</td>
<td>17.4</td>
<td>1291</td>
<td>1263</td>
<td>65</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>20.5</td>
<td>20.5</td>
<td>1317</td>
<td>1263</td>
<td>72</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>21.0</td>
<td>23.5</td>
<td>1357</td>
<td>1409</td>
<td>69</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>24.1</td>
<td>26.6</td>
<td>1382</td>
<td>1409</td>
<td>74</td>
</tr>
<tr>
<td>9.1</td>
<td>7.0</td>
<td>75</td>
<td>30.0</td>
<td>32.7</td>
<td>1426</td>
<td>1409</td>
<td>81</td>
</tr>
</tbody>
</table>

- **M** = moisture content (w.b.); **H** = silo height; **liq** = liquid; **tot** = total; **D** = diameter of silo
- **simul** = simulation
- *Lateral pressure calculated with the saturation height from Eq. 6 (col. 11)
in the three largest silos. At 65%, only the three smallest silos indicated no saturation at all. At 70% and 75% moisture contents, all silos considered showed some saturated silage. At 75% moisture content the simulated saturation heights were very close to the overall height of the silo. This means that the design for this situation should be similar to that of a water reservoir of the same size. This is in fact what the code in the Netherlands recommends for silage having 75% moisture content and over.

The parametric study shows clearly that in silos with significant liquid pressures a good estimate of the saturation height is needed to provide a good estimate of the liquid pressure and hence the total pressure. Tables I and II show that the 1990 CFBC generally estimates smaller values for the saturation height than the simulations indicate. Consequently, it generally underestimates maximum pressures in undrained silos (Table II). For drained silos the CFBC values are often quite good but the shape of the pressure diagram is quite different from that predicted by the numerical analyses. The CFBC has the maximum pressure at the silo floor as for an undrained silo; the analyses indicate that the maximum in drained silos is well above the floor.

From the results of the parametric study of drained silos (Table I, col. 4) a prediction equation for the saturation height, \( H_s \), was arrived at:

\[
H_s = 1.1H + 1.2M - 95 \quad 60\% < M < 75\%
\]

\[
2.5 < H/D < 4
\]

where \( H_s = H - z_s \) = saturation height measured from silo floor
Table II. Simulated saturation heights and maximum pressures in undrained silos

<table>
<thead>
<tr>
<th>H (m)</th>
<th>D (m)</th>
<th>M (%)</th>
<th>Saturation height simul</th>
<th>Saturation height CFBC</th>
<th>Bulk density (kg/m³) simul</th>
<th>Bulk density (kg/m³) CFBC</th>
<th>Maximum pressure (kPa) Simulation</th>
<th>Maximum pressure (kPa) CFBC Eq. 2</th>
<th>Saturation height (m) Eq. 7</th>
<th>Maximum Pressure (kPa) Eq. 2</th>
<th>Ratio col 12 col 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>3.7</td>
<td>65</td>
<td>691</td>
<td>721</td>
<td>3.4</td>
<td>0.0</td>
<td>17</td>
<td>9.0</td>
<td>17</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>4.9</td>
<td>65</td>
<td>12.2</td>
<td>812</td>
<td>9.1</td>
<td>65</td>
<td>3.3</td>
<td>33</td>
<td>60</td>
<td>27</td>
<td>1.21</td>
</tr>
<tr>
<td>27.4</td>
<td>9.1</td>
<td>65</td>
<td>27.4</td>
<td>937</td>
<td>15.9</td>
<td>65</td>
<td>156</td>
<td>94</td>
<td>15.9</td>
<td>162</td>
<td>0.81</td>
</tr>
<tr>
<td>12.2</td>
<td>3.7</td>
<td>70</td>
<td>4.7</td>
<td>900</td>
<td>11.2</td>
<td>0.0</td>
<td>46</td>
<td>64</td>
<td>21</td>
<td>5.2</td>
<td>55</td>
</tr>
<tr>
<td>18.3</td>
<td>4.9</td>
<td>70</td>
<td>18.3</td>
<td>989</td>
<td>20.1</td>
<td>3.2</td>
<td>110</td>
<td>135</td>
<td>49</td>
<td>11.3</td>
<td>109</td>
</tr>
<tr>
<td>27.4</td>
<td>9.1</td>
<td>70</td>
<td>27.4</td>
<td>1100</td>
<td>20.1</td>
<td>6.6</td>
<td>197</td>
<td>248</td>
<td>165</td>
<td>20.4</td>
<td>205</td>
</tr>
<tr>
<td>12.2</td>
<td>3.7</td>
<td>75</td>
<td>8.8</td>
<td>1047</td>
<td>14.8</td>
<td>5.8</td>
<td>86</td>
<td>106</td>
<td>59</td>
<td>9.7</td>
<td>96</td>
</tr>
<tr>
<td>18.3</td>
<td>4.9</td>
<td>75</td>
<td>18.3</td>
<td>1168</td>
<td>14.8</td>
<td>13.2</td>
<td>145</td>
<td>176</td>
<td>125</td>
<td>15.8</td>
<td>157</td>
</tr>
<tr>
<td>27.4</td>
<td>9.1</td>
<td>75</td>
<td>27.4</td>
<td>1336</td>
<td>23.6</td>
<td>26.6</td>
<td>231</td>
<td>293</td>
<td>283</td>
<td>24.9</td>
<td>259</td>
</tr>
</tbody>
</table>

M = moisture content (w.b.); H = silo height; liq = liquid; tot = total; D = diameter of silo

simul = simulation

b Lateral pressure calculated with the saturation height from Eq. 7 (col. 11)

(m). Both M and H are significant at the 1% level. Zero and negative values for Hs from Eq. 6 should be interpreted as no saturation. Table I shows the values calculated with Eq. 6 in column 11. Figure 5 shows a plot of Hs determined with Eq. 6 versus the simulated values (Table I, col. 4).

The pressures in silos in which no saturation occurred are fairly typical Janssen (1895) type curves. In drained silos (see Figs. 2 and 3) the pressures from those simulation analyses in which saturation of the silage was indicated are significantly different below the saturation level because of the addition of the liquid pressure. The total pressure curves below the saturation level have common characteristics. Just below the saturation level the pressures increase at a rate of about 10 kPa/m, the increase due to liquid pressure plus the relatively small rate of increase in effective pressure. The rate of increase in pressure reduces fairly quickly with depth down to the point of the maximum pressure which lies typically between one half to one third of the saturation height from the bottom of the silo. Below the point of maximum pressure the liquid pressure quickly reduces to zero and the total pressure to the value of the effective pressure.

In undrained silos the effective pressure is about the same as in drained silos. However, the hydrostatic pressure, and hence the total pressure, is significantly greater and the maximum occurs near the silo bottom (see Fig. 4). Table II shows the maximum total pressures from the simulation without a drain in column 9. The maximum liquid pressures are shown in column 8. As well, the saturation height (col. 4) tends to be somewhat greater than for drained silos. It can be estimated reasonably well by:

\[ H_s = H + 0.9M - 70 \quad 65% < M < 75% \]
\[ 2.5 < H/D < 4 \]

Table II includes the values of saturation height calculated with Eq. 7 in column 11. As well, Table II shows in column 12 the maximum pressures calculated from the CFBC recommendation (Eq. 2) using the silage densities recommended by that code but using saturation heights determined by Eq. 7. Both Eq. 2 and the simulations show the maximum pressure to occur at the silo floor.

A comparison of the values of maximum pressure from the simulations (column 9, Table II) with those predicted with Eq. 2 (column 12, Table II) shows that this expression is fairly good for undrained silos. The ratio of predicted over simulated maximum pressures is shown in column 13 of Table II. The ratios range from a value of 0.81 to 1.21; the mean of the ratios for the nine analyses is 0.93, the standard deviation is 0.15. Thus, the continued use of Eq. 2 for undrained silos seems to err somewhat on the unsafe side, assuming of course that the simulations are realistic. However, the authors consider that Eq. 2 is adequate for design, bearing in mind that no silo is fully watertight.

The maximum pressures in a drained silo occur somewhere between the saturation level and the silo floor. When a silo is properly drained, no increase in liquid pressure occurs below a point about halfway between the saturation level (Eq. 6) and the bottom of the silo. The authors recommend that for adequately drained silos, Eq. 2 be used to calculate lateral pressures down to halfway between saturation level and the silo bottom. It is also recommended that below that level the total pressure be kept constant. Thus:

\[ P_t = P_s + (z-z_s)(11.0 - \frac{4uK}{D} P_s) \quad z_s < z < (H + z_s)/2 \]
\[ P_t = P_s + 0.5(H - z_s)(11.0 - \frac{4uK}{D} P_s) \quad (H + z_s)/2 < z < H \]

The resulting maximum pressures are included in column 12 of Table I. The agreement of these recommended maximum pressures with the total pressures from analyses of the
Drains in the bottom of a silo have to be adequately large to carry away the silage juice that flows downward through the silage mass. The rate of flow is a function of the silage type, silo size, and of the moisture content of the silage. In most silos the density of silage near the floor is in the order of 900 - 1100 kg/m³. At these densities the vertical hydraulic conductivity of the silage will be of the order of 10⁻⁷ to 10⁻⁸ m/s (Tang and Jofriet 1991). It is obvious from these low values that the rates of flow will usually be small and the common provisions made today by silo builders are as a rule adequate providing they are kept in working order.

The hydrostatic pressures against a silo wall will, of course, develop only if the wall is watertight. It is therefore not necessary to use the design pressures proposed in this paper for stave silos providing the owner is prepared to have silage juice draining through the joints between staves; however, this will shorten the life of a stave silo because of corrosion of the staves and the steel hoops.

**SUMMARY**

The results of an extensive parametric study of silo wall loads due to wet silages were used to formulate some improvements to the present provisions of the 1990 Canadian Farm Building Code (NRC 1990). This code has provisions for dealing with wet silages. However, the height of the saturation zone appears to be underestimated. Two new expressions, Eqs. 6 and 7, are proposed for estimating the saturation height in tower silos with and without drainage. The CFBC does not provide for the considerable reduction in liquid pressure resulting from floor drains. A simple modification to the present code is recommended (Eqs. 8 and 9).

**ACKNOWLEDGEMENTS**

The funding for this project was provided by the Natural Sciences and Engineering Research Council of Canada and the Ontario Ministry of Agriculture and Food.

**REFERENCES**


ISA. 1981. ISA recommended practice for the design and construction of top unloading monolithic concrete farm silos. International Silo Association, Des Moines, IA.


JOFRIET, YAO and NEGI...


