Design criteria for structural design of silage silo walls

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Abstract

Existing Swedish design guidelines (JBR) cover silo wall heights up to about 3 m. These guidelines presumably overestimate the forces and pressures exerted by silage juice when silo walls are more than 3 m high, which could result in over-sizing, material waste and increased capital costs. This study determined silage physical properties in terms of horizontal wall pressure and evaluated silage juice levels in silos with a wall height of 3 m or more.

Wall pressure was measured by transducers mounted on a steel ladder rack placed vertically along the internal silo wall. The ladder rack also permitted measurement of silage juice levels in slotted steel pipes. The pressure on the transducers was recorded by a data acquisition system displaying static and total loads (pressures imposed by silage material without and with the compaction machine, respectively).

The static pressure at the bottom of the silo wall (4 m) was 16 kPa during filling and compaction, and 22 kPa 1-4 months after filling. The silage juice did not interact with compaction. The wall pressure increased by 30% after filling, but the increase was only significant at 1 m from the silo bottom. The dynamic load was 17 kPa when the compaction machine passed 0.1 m from the silo wall.

New guidelines are proposed based on the results and on the Eurocode for ultimate limit states (ULS) for two stages; filling and the utility period. The design bending moment for ULS was 21% lower than specified in JBR.

Key words: bunker silo, wall, silage, pressure, force.

1. Introduction

1.1 Problem description

There is growing interest among farmers in increasing their local production of animal feed since this can reduce transport and therefore the climate carbon footprint. A large amount of the roughage used by Swedish livestock is silage based on grass and maize, which is stored in bunker silos. A typical bunker silo consists of a concrete slab and in-situ or precast concrete or wood wall panels. In the past bunker wall height in Sweden were typically 2-3 m, but in recent years bunker silos with wall heights of 4 m or higher have become more common. Investment in bunker silos has doubled in Sweden during the last 10 years.

The structural design of silo walls is based on the horizontal loads exerted by the silage during silo filling and storage. The hydrostatic load from the silage juice also has to be considered. The magnitude of this latter load is entirely dependent on the level to which the silage juice rises in the silo. In the Swedish design guidelines, JBR (SJV, 1995), the silo wall pressure exerted by the silage juice is taken to be the corresponding pressure arising from having a similar amount of water in the silo.

Nomenclature

Bunker silo	A silo consisting of a concrete slab and in-situ or precast concrete or wood wall panels.
Hydrostatic load	Load resulting from silage juice.
DM	Silage dry matter (%), mainly depending on moisture content, fibre content, forage chopping length and processing.
Visco-elastic material	Silage is a visco-elastic material, conceptually consisting of masses, springs and voids and liquid.
Horizontal pressure (q)	Horizontal forces acting on a silo wall (Nm^{-2} or Pa).
TE	Silage surface top edge.
z	z is the distance from compacted surface top edge (TE) to the level where the pressure is to be calculated (m).
Point load (F)	Load concentration in one point (N).
ULS	Ultimate limit states according to Eurocode 0, see Table 1.
ψ	Combination factor, ψ, which reduce the design values of variable loads when they act together, ψ = 0 - 1.0.
γ_d	For ULS design using the partial factor method of EN 1990 to EN 1999, the safety class for a structural element is taken into consideration by using the partial factor γ_d as follows: safety class 1-3, γ_d = 0.83 -1.0.
Compaction vehicle	Usually a farm tractor used for silage compaction in the silo.
Q_{tot}	Pressure sensors recording of the load against the silo wall when a compaction machine is passing (Pa).
Q_{stat}	Wall load recorded without a compaction machine in the vicinity (Pa).
Q_{dyn}	Dynamic load from the compaction machine: $Q_{dyn} = Q_{tot} - Q_{stat}$ (Pa).
Dead load	Vehicle self-weight (N).

1.2 Literature and preliminary work

Although silage is no longer harvested in its unwilted form in Sweden, as a result of location the silage juice levels can vary considerably between cuts within the same farm. Variations in silage drymatter (DM) at harvest are probably higher in Scandinavia than in the rest of Europe because there can be more precipitation in periods with lower temperatures, making forage drying slower, especially in autumn (Savoie et al., 2002).

A number of factors determine the density of DM and thus the amount of silage juice. Factors include: moisture content, fibre content, forage chopping length and processing, but

DM level is mainly dependent on the moisture content of the crop at harvest (Stewart & McCullough, 1974; Savoie et al., 2002; Schemmel et al., 2010).

According to O'Donnell (1993), silage juice level and flow are completely dependent on the silo construction and drainage system. Factors that determine the drainage flow from the silo are the pressure within the silo, material permeability and whether a proper drainage system is installed. A typical amount of silage juice from grass silage at 18% DM is 150 l t^{-1} (Stewart & McCullough, 1974), whereas bunker grass silage with DM ≥ 30% produces very little or no silage juice (Bastiman, 1976).

Silage is a visco-elastic material (Tang et al., 1987b), conceptually consisting of masses, springs and voids and liquid. The spring properties depend upon the type of silage material. The voids in the silage can be divided into two categories, macro and micro voids. Macro voids are the spaces between cut fibres, while micro voids consist of the cellular structure of the plant material, where the moisture is mainly contained. Under load, the micro voids become too small to contain the liquid and it starts to be expelled as free liquid. If the DM is lower than 35%, the silage in the lower part of the silo is likely to become saturated, resulting in silage juice (Tang et al., 1987a). The expelled juice usually seeps through the silage and drains out of the silo, causing nutrient losses and environmental problems (Tang et al., 1987b). The estimated level of silage juice in a silo is of critical importance for its design; the amount of building materials required in the structural design of the walls and their attachment to the concrete slab.

The Swedish guidelines are based on extremely high loads compared with international design guidelines (Fig. 1) and research findings (Nilsson, 1982; LBS, 1983; Kangro, 1986; Negi & Jofriet, 1986; Martens, 1993; SJV, 1995; Gruyaert et al., 2007; Van Nuffel et al., 2008). In ASABE (2008), the design loads do not include hydrostatic load, but they do include the mass bulk density of the silage as a factor in the silo wall pressure calculations. Silage pressure normal to the wall is determined as an equivalent-liquid pressure (Zhao & Jofriet, 1991, 1992). However, it can be assumed that the design loads of today are different from these assumptions since different types of silage and heavier compaction machines are being used.

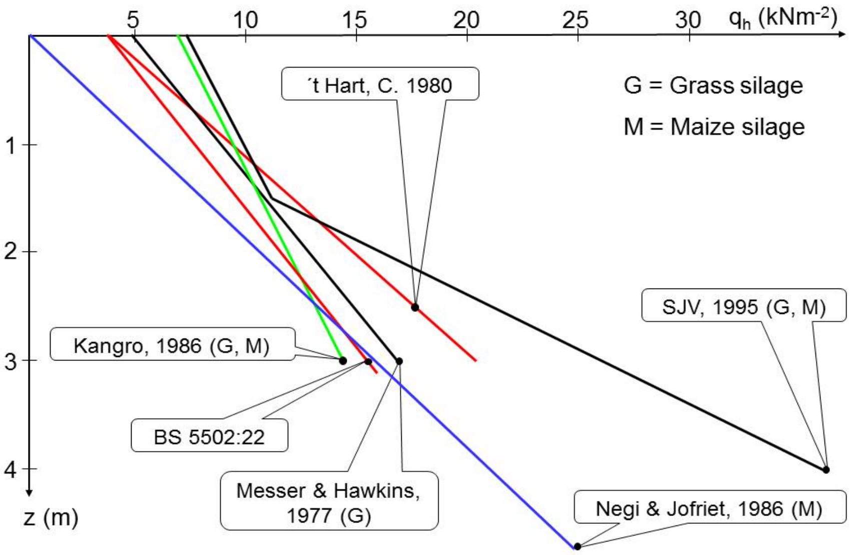


Fig. 1. Current JBR guideline (SJV, 1995) compared with other guidelines and recommendations for silo wall load. The vertical axis (z) represents the distance below the silage top surface and the horizontal axis (q_h) the horizontal pressure on the silo wall given in different guidelines.

A preliminary investigation showed that Swedish guidelines (SJV, 1995) specified higher design loads than international guidelines for silo wall heights of 2 m or more. For example, for a silo wall height of 4 m, the design load in the guidelines is approximately twice that stated in other sources.

At present, work is underway at the Swedish Standards Institute (SIS) to revise the standard on bunker silos and the guidelines on bunker silo design. For this work, new supporting data are needed. Altogether, the current evidence indicates that the Swedish design guidelines are incorrect, e.g. the actual pressure from the silage juice is probably considerably lower. More exact and reliable values need to be determined using field measurements.

1.3 Existing building codes related to bunker silo design

The present Swedish design guidelines, LALT (LBS, 1983) and JBR (SJV, 1995), were developed for bunker silos of up to 3 m height. With increasing wall height they are no longer applicable, but they are still used in the absence of other relevant design guidelines.

These guidelines specify a load from the silage itself, but also a pressure from silage juice corresponding to a water column level of 1.5 m below the maximum silage filling level. This silage juice level is based on measurements by Kangro (1986) carried out during filling of a silo with a wall height of 2 m. However, the validity of these measurements can be questioned. The effect of this extra load is less important with lower wall height, but at 4 m or more the over-dimensioning can be considerable since practical experience has shown that the extra pressure from silage juice appears to be overestimated. The outflow of silage juice does not appear to be of the order assumed since unwilted silage is no longer harvested in Sweden.

According to JBR (SJV, 1995) the following equations apply:

Horizontal pressure, q_{hk} on the silo wall (variable load with $\psi = 1.0$).

$q_{hk} = 7.5 + 2.5 * z$ kN m^{-2} for $0 < z < z_0$
$q_{hk} = 7.5 + 2.5 * z + 7.5\ (z-z_0)$ kN m^{-2} for $z_0 < z < 4$ m

where
z is the distance from compacted surface top edge (TE) to the level where the pressure is to be calculated, and

z_0 is the distance from compacted surface TE to the maximum silage juice level. The normal silage juice level is regarded as being 1.5 m below TE for silos without a drainage system.

In addition, two point loads caused by the compaction machine should be considered, each amounting to $0.1 \times T$ kN, or at least 6 kN, where T is the total weight of the compaction machine. These point loads are assumed to act at level $z = 0.6$ m below TE with a centre-to-centre distance of 2.5 m (SJV, 1995). The point loads are regarded as variable, with $\psi = 0$.

Eurocode design guidelines (Eurocode, 2010) define four different ultimate limit states (ULS), which must be verified when relevant to the situation in question (Table 1).

1.3.1 Loads and load combinations

The compaction machine is regarded as a variable load with a combination factor $\psi_0 = 1.0$.

Pressure from soil on the bunker silo wall is regarded as a permanent geotechnical load.

Load from a vehicle outside the silo is regarded as a variable geotechnical load.

According to EKS 8 (Boverket, 2011), the calculation is made in safety class 1 ($\gamma_d = 0.83$; i.e. minor risk of serious personal injury).

Table 1. Ultimate limit states (ULS) according to Eurocode 0 (Eurocode, 2010).

Terms in Eurocode 0	Description
EQU (Equilibrium)	Loss of equilibrium of the structure (or part of it), considered as a rigid body.
STR (Structure)	Interior failure or deformation of the structure (or part of it), where the material strength is decisive.
GEO (Geo stability)	Failure or excessive deformation in supports and foundations, where strength of earth or rock is decisive.
FAT (Fatigue)	Failure caused by fatigue of the structure (or part of it).

1.3.2 Filled silo with soil pressure

Using the Eurocode for ULS (Table 1), a load combination of structure and geo stability (STR/GEO), set B, equations 6:10a and 6:10b must be complied with, using soil pressure according to STR/GEO and equation 6:10 set C (favourable value) (Eurocode, 2010). Possible vehicular traffic outside the silo should also be considered.

1.3.3 Empty silo with soil pressure

Again, using the load combination STR/GEO, set B, equations 6:10a and 6:10b must be complied with, with soil pressure according to STR/GEO and equation 6:10 set C (unfavourable value) (Eurocode, 2010). Possible vehicular traffic outside the silo should also be considered.

1.3 Aims and objectives

The overall aim of this study was to provide data to support new guidelines on designing bunker silo walls suitable for on-farm storage of silage at an economical price for the farmer.

Specific objectives were to determine silage physical properties of importance for the horizontal wall pressure and evaluate the maximum silage juice level in silos with a wall height of 3 m or more. The data obtained were intended to form a basis for new national design guidelines and a revised Swedish standard. The ultimate goal was to lower the investment costs for silage bunker silos. The starting hypothesis was that the existing design guidelines overestimate the loads originating from silage and silage juice.

2 Materials and methods

2.1 Measuring system

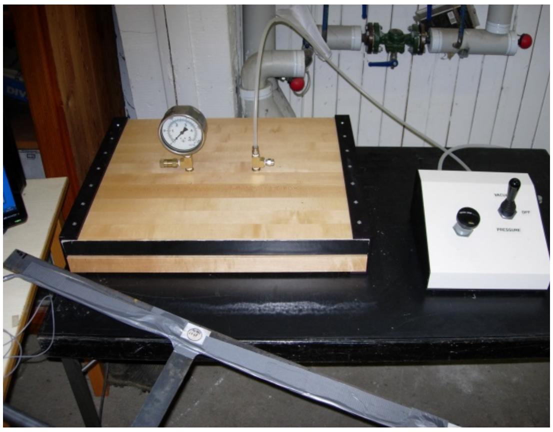
The measuring system consisted of two ladder racks, each with four pressure sensors. These were placed vertically along the internal face of the silo wall from the bottom to the top. The load sensors (FSR A401, TEKSCAN Inc., Boston, USA) were less than 1 mm thick and were mounted on the rack at a spacing of 1.0 m, with the first sensor at 0.05 m from the silo bottom (Fig. 2).

The sensors were individually connected to a amplifier and a computer-based measuring programme (DataLink type NOS. DLK 900, Biometrics Ltd, Gwent, UK), from which the data were imported to Microsoft Excel. The system recording rate was 0.1 Hz and the pressure range was 0-34 kPa.

2.2 Calibration

Each sensor was calibrated individually by a standardised 5 PSI 18” x 20” bladder (PB5B, TEKSCAN Inc., Boston, USA) with load increasing step-wise from zero to 28 kPa. A calibration equation was determined for each sensor. To protect them from the corrosive effects of silage juice, the sensor cable connections were sealed with silicone. Malfunction of sensors due to silage juice has been reported by Kangro (1986) and Zhao and Jofriet (1991). After sealing, the sensor was calibrated again before being mounted on the ladder rack. The sensor was then attached, with adhesive tape on both sides, to the flat steel part of the ladder. The sensor connection and cable were also fastenened using tape (Fig. 2).

a)



b)

Fig. 2-a) Bottom sensor mounted on the measuring rack with a slotted pipe to the left. **b**) calibration bladder by which the sensors was loaded at different pressures.

2.3 Measurement procedure

Information concerning the distance from the wheel to the silo wall, and direction of travel, were obtained from the driver of the compaction machine through a signal when starting to compact the silage close to the silo wall and during track-by-track compaction between the silo walls. The tracks were recorded with information on place, time, starting point distance to the silo wall, silage height, type of compaction machine and number of tracks, following the procedure described by Kangro (1986). To provide an explanation of the wall pressure and silage juice level, the method of compaction, weight and tyre width of the compaction machine and silo packing procedures were recorded alongside these measurements. Fibre type and silage chop length information were obtained from the farmers. Silage DM content was obtained from silage analysis. Fibre type and silage chop length did not differ between farms and these were therefore omitted from the analysis.

A measurement sequence started by measuring the static load from the silage. Thereafter, the number of tracks by the compaction machine was recorded and at the end of the process the static load was measured again. The criterion for a successful measurement sequence was that the static load at the start and the finish should have the same value (Kangro, 1986).

2.4 Experiment design

The combined silage juice level and silage wall pressure profile measurements were performed during the 1st to 4th harvests of wilted grass and maize silage. These measurements were conducted in bunker silos with no drainage system and a wall height of 3-4 m, on farms in the Swedish provinces of Västergötland, Skåne and Öland (Table 2).

Table 2. Dimensions of the silos from which the silage juice level and silo wall pressure measurements were conducted during two seasons.

Silo dimensions

	Borås	Falköping	Klippan	Skurup	Svalöv	Varberg	Öland	Önnestad
Length, m	30	30	42	15	15	42	30	12
Width, m	12	12	10	6	6	10	12	6
Height, m	4	4	4	3	3	3	3	2

The silage juice level was determined using a measuring stick, measuring the juice level inside slotted 16-mm steel pipes placed vertically along the silo walls as single pipes, or as part of a steel ladder rack (Fig. 3). The measurements were performed during two harvesting seasons. In the first season, the measurements were conducted by farmers during the first 14 d after filling in 14 silos using six evenly distributed pipes in each silo. In the second season, the measurements were conducted monthly by the researchers in 10 silos during 1-4 months after filling, depending on harvest date, using two pipes and two ladder racks. By combining data on silage juice level and silage wall pressure during a longer period of time after harvest, changes in wall pressure could be studied over time. To examine the correlation between silage juice and silage DM, a regression calculation was performed in Minitab™ (Minitab, 2007).

The vertically-placed pressure sensors recorded the static load against the silo wall at different levels, both during filling and afterwards. The total load from the silage material and from the passing compaction vehicle (usually a farm tractor) was recorded by the pressure sensors at different levels during silo filling.

The load (Q) recorded when the compaction machine was passing was designated total load (Q_{tot}) and the load recorded without the compaction machine in the vicinity was designated static load (Q_{stat}). The extra (dynamic) load from the compaction machine (Q_{dyn}) was thus: $Q_{dyn} = Q_{tot} - Q_{stat}$.

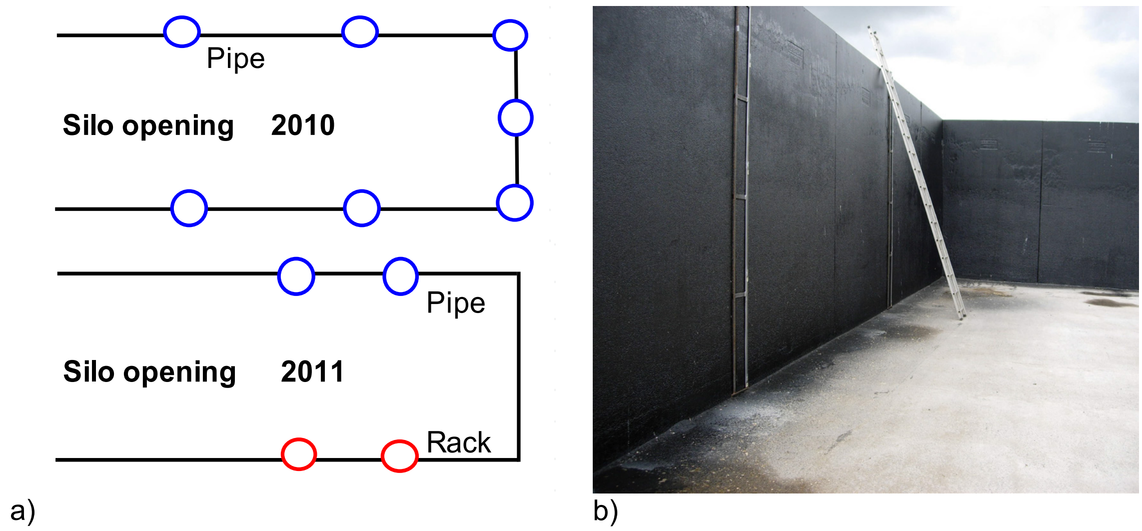


Fig. 3-a) Placement in silo of 16 mm slotted measuring pipes for silage juice in 2010 where the distance between pipes was in proportion to silo length (approximate distance of 10 m apart) as seen from above. **b**) Measuring rack placed vertically along a silo wall, 6 m apart and 6 m from silo end in 2011.

The silos were filled with silage in layers of approximately 0.25 m at a time, distributed over half the silo surface. The material was compacted by driving the compaction machine track-by-track across the surface 2-4 times for every new silage layer. A series of measurements was conducted for each silage layer at filling. During each series, Q_{stat} and Q_{tot} values were recorded for the silage material and the compaction machine at different distances from the silo wall (0.10 m, 0.20 m etc.) and at different silage heights above the load sensors. This resulted in a load profile of Q_{stat} and Q_{tot} values for the silo wall. Q_{dyn} values were calculated and grouped according to distance to the silo wall.

The weight of the compaction machines used in the study was 11.2-14.5 t, with a tyre width of 0.5 m.

2.5 Data recording and processing

The raw values were imported from the measuring programme to Microsoft Excel. The data were examined in chronological order to find Q_{tot} and Q_{dyn} values. Mean and standard deviation (SD) were calculated for each sensor and static load value (n = 100-300), which gave a mean coefficient of variation of 110%. After locating the Q_{tot} for the individual crossing by the compaction machine, five measurement values were used to represent the local maximum value, in order to eliminate the possibility of temporary measurement error by the sensor.

The static load values from the individual measuring series were compiled to one static load profile from all the individual silo measurements. The Q_{stat} measurements after filling were treated in the same way as those made during filling.

The Q_{dyn} value was calculated for each of the five total load values through subtraction of the corresponding static load value, after which a mean value was calculated for Q_{dyn}. For each load sensor, a maximum value was compiled for every 0.5 m silage mass above the sensor at different distances of the compaction machine to the silo wall (0.1-1.5 m). The maximum values recorded by the sensors were compiled in a Q_{dyn} matrix including all silo measurements.

The 95th percentile was calculated for the load values representing the same level below the silage surface for Q_{dyn} and Q_{stat} values at filling and Q_{stat} after filling, through which a trend curve was drawn. By logarithmic transformation of the Q_{dyn} maximum values, a normal distribution was obtained and a regression curve could be drawn. Using the regression curve, the 95th percentile was calculated for the Q_{dyn} values, which were transformed back via exponential function calculation.

For each sensor level the Q_{stat} values after filling were tested to determine whether they were affected by the silage juice level. The data were divided into two groups, with silage juice included in one group but not in the other. A paired t-test was used to check for significant differences between the two groups. A significance level of 5% was used in the analysis.

3. Results

3.1 Silage juice measurements

In 2010 the variation in silage juice level was high, which reflected the harvesting conditions. In order to determine whether a measuring period of 14 d was relevant, and whether silage juice remained in the silage material, additional measurements were carried out in silos which gave low DM values in previous measurements. The results from three silos showed that 78-

89% of the silage juice remained 4-5 months after filling. As a result, it was decided to extend the silage juice measurements for several months after filling, along with silo wall measurements in the next season. The silage juice level increased in six out of 10 silos during the 3 months after filling and remained at the same level in 90% of the unopened silos in 2011 (Table 3).

Table 3. Silage juice level measurements during two seasons in 24 bunker silos. Mean juice level value represents 6 measurements per occasion in each silo during 14 days after filling in 2010, and 4 measurements per occasion in each silo approx. once per month during 1-4 months after filling in 2011 (mean and standard deviation (SD)).

Silage juice level measured from silo bottom at filling, m								
Harvest, year	Borås, 4 m Mean (SD)	Falköping, 4 m Mean (SD)	Klippan, 4 m Mean (SD)	Skurup, 3 m Mean (SD)	Svalöv, 3 m Mean (SD)	Varberg, 3 m Mean (SD)	Öland, 3 m Mean (SD)	Önnestad, 2 m Mean (SD)
1, 2010	0.53 (0.17)	0.74 (0.82)[a]		1.70 (0.12)	1.00 (0.23)		1.38 (0.12)	0.13 (0.06)
2	2.03 (0.25)	1.02 (0.27)			1.00 (0.11)		0.00 (0.00)	
3		3.10 (0.50)[b]					0.00 (0.00)	
4		1.70 (0.40)[c]				1.37 (0.14)		
1, 2011		2.14 (0.28)[d]	1.90 (0.11)[d]				0.02 (0.03)	
2		2.51 (0.55)	2.70 (0.13)[d]					
3		0.48 (0.21)[d]	0.03 (0.05)				1.26 (0.36)	
4		1.45 (0.02)[d]	0.59 (0.41)[d]					

Recorded level after [a)] 5 months, 1.90 (0.58); [b)] 1.4 months 2.80 (0.40); [c)] 1 month 1.90 (0.50); [d)] increased juice level 1.5 month after filling

The mean silage juice level was 40% of the silo wall height for the 24 silos that were included in the measurements in 2010 and 2011. The highest silage juice level was 78% of wall height, recorded in one silo. The highest design value for silage juice level after filling according to Kangro (1986) was exceeded in four and three cases for 3 m and 4 m silo wall height, respectively. The mean silage juice level for the silos included in the measurements in 2011 was 43% of silo wall height. A direct correlation was obtained between silage juice level and silage DM (silage juice = 2.788 - 0.05293 × DM, $p = 0.012$), i.e. the higher the DM, the lower the silage juice level.

Table 4. Dry matter (DM) measurements during two seasons in 24 bunker silos.

Dry matter in silos of different wall heights, %								
Harvest, year	Borås, 4 m	Falköping, 4 m	Klippan, 4 m	Skurup, 3 m	Svalöv, 3 m	Varberg, 3 m	Öland, 3 m	Önnestad, 2 m
1, 2010	42	31-32		27-30	28		26	28-35
2	35	32-41			21		44	
3		24					59	
4		22-23				31-32		
1, 2011		29	27				42	
2		24	27					
3		29	29				27	
4		39	30					

3.2 Load profiles

Measurements of load profiles were carried out during silo filling with wilted grass and maize silage at 10 silos during 2011, with approximately 400 load profiles at each silo filling. Figure 4 illustrates a typical load profile and the extra load from the compaction machines at filling. The static load profile is the result of the pressures imposed by silage material and silage juice. However, no silage juice was observed during filling.

For the load profile illustrated in Fig. 4, the maximum silage juice level was reached 3 months after filling (50% of silo wall height).

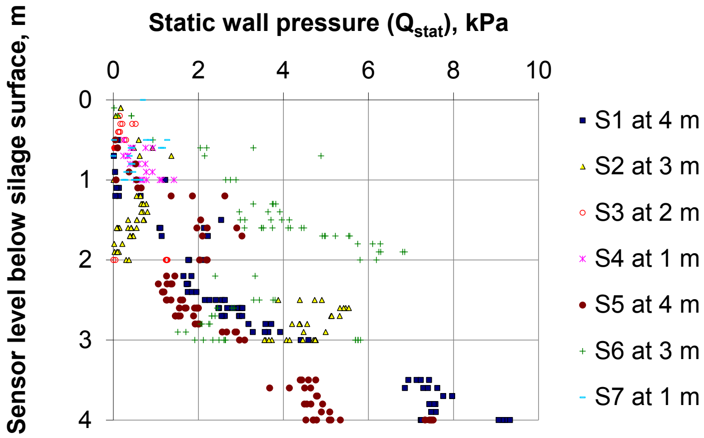


Fig. 4-a. Example of static wall pressure load profile on a 4 m high bunker silo wall at first grass harvest with DM 27% and 591 recorded measuremets from 7 sensors (S) placed at 1-4 m below the silo wall top.

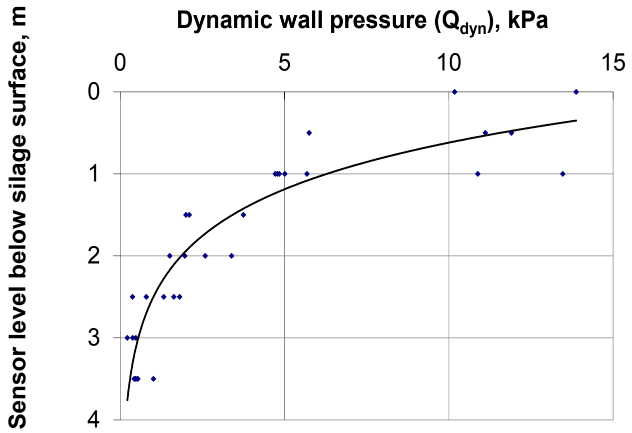


Fig. 4-b. Example of dynamic wall pressure on the silo wall from the compaction machine (11.2-14.5 t) passing 0.1 m from the silo wall (4 m). The values show the load when the machine passes by the silo wall at different heights above the sensor positions.

3.3 Static load

The results from four complete fillings of wilted grass and maize silage formed the basis of the total static load profile Q_{stat} (n=2543), where the 95th percentile was calculated for each individual load level (Fig. 5). A trend line drawn through the 95th percentile shows, with 95% probability, the minimum size of load to which the silo wall load is exposed. The Q_{stat} maximum was 16 kPa at filling and 22 kPa 1-4 months after filling at a depth of 4 m.

When Q_{stat} was measured after filling, it was found that the silage juice level had increased over time. The effect of the silage juice level was statistically significant for the load cells 1 m from the silo bottom, but not for any of the other levels (Table 5).

In calculating the 95th percentile for the measurement values compiled after filling (n=151) to a total load profile, it was evident that Q_{stat} after filling in seven silos was higher than Q_{stat} at filling, by on average +56% at 1 m, +36% at 2 m, +24% at 3 m and +37% at 4 m under the silage surface. Alongside the trend line of the 95th percentile in Fig. 6, the former design guideline JBR (SJV, 1995) is added for comparison.

Table 5. Effect of silage juice on silo wall pressure at sensor level at filling and 1-4 months after filling in seven bunker silos (number of samples (n), means and standard deviation (SD)).

Level, m[a]	At filling, no silage juice		1-4 months after filling, with silage juice		
	n	Pressure, kPa Mean (SD)	n	Pressure, kPa Mean (SD)	p[b]
1	11	5.25 (7.08)	11	4.54 (4.91)	0.703 ns
2	11	7.82 (8.02)	11	6.97 (7.72)	0.790 ns
3	11	4.86 (4.82)	11	10.12 (3.06)	0.024 *
4	11	10.52 (6.68)	11	13.59 (4.03)	0.105 ns

a) sensor level in metres from silage surface

b) Significance level comparing silo pressure at filling and after filling: * = $p < 0.05$, ns = non-significant.

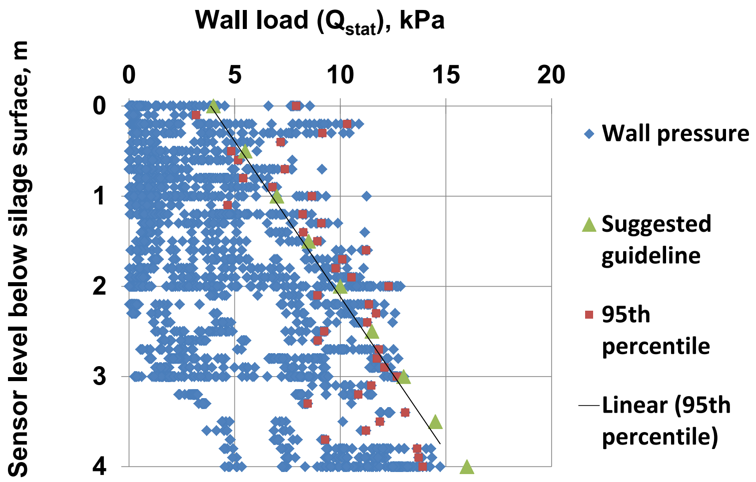


Fig. 5. Static silo wall load (Q_{stat}) in state 1 (filling) with 95th linear percentile. The design load should be chosen to the right of the 95th percentile trend line, i.e. as indicated by the green triangles.

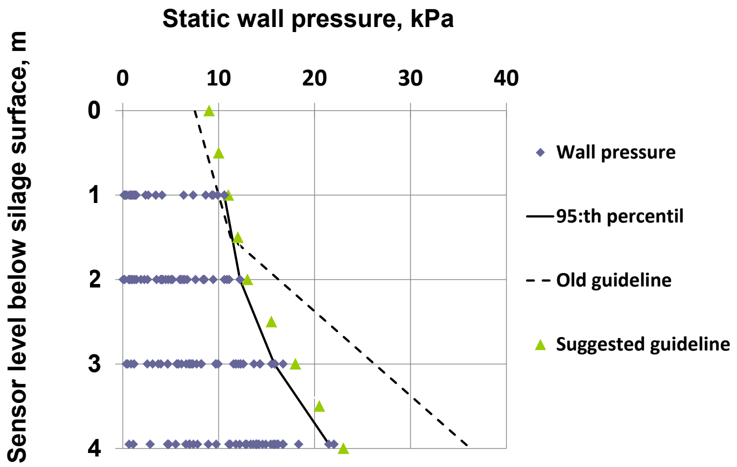


Fig. 6. Static silo wall load (Q_{stat}) in state 2 (silage load with silage juice, 1-4 month after filling), with 95th linear percentile. The design load should be chosen to the right of the 95th percentile trend line, i.e. as indicated by the green triangles. The dashed line indicates the previous guideline.

3.4 Dynamic load

Of all the different load profiles from the compaction machine (Q_{dyn}), those with the smallest distance to the silo wall (0.1 m) had the highest values, and consequently the others are not shown. The load was largest 0.5-1 m below the silage surface and from there it decreased downwards in the silage material. The load from the compaction machine acted similarly on the silo wall from the start of filling at the silo bottom until the silo had been totally filled. When the silo was totally filled, the wall load from the compaction machine reached its maximum (Fig. 7). The trend line drawn through the 95th percentile shows, with a probability of 95%, the maximum silo wall load, i.e when the load values are below the line. The maximum Q_{dyn} (n = 6431) according to the 95th percentile was 17 kPa.

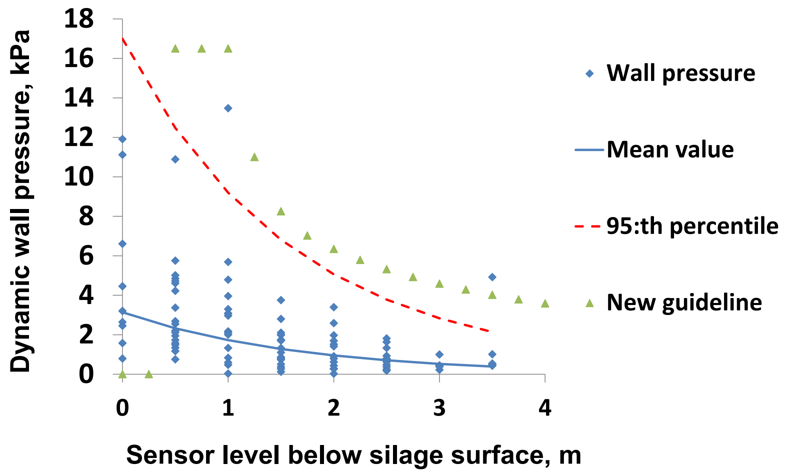


Fig. 7. Load exerted by the compaction machine at 100 mm from the silo wall. Mean maximum value calculated for each 0.5 m silage level for all load sensors. The dashed line shows the 95th percentile and the green triangles show 0.15 × dead load of the compaction machine with least load width of 1.0 m and with a load distribution of 1:1. In calculating the load distribution, it was assumed that no overlapping occurred.

3.5 New design guidelines

3.5.1 Load model conditions

Based on the results obtained here, a load model for new design guidelines was devised for bunker silo walls, using a 20-year design working life. Compared with JBR (SJV, 1995) the following could be noted:

- The silage juice level only has an impact after filling and this impact is not connected with the use of the compaction machine
- The impact from the compaction machine on the silo wall is exerted from 0.5 m below the silo TE and downwards

3.5.2 Ultimate limit states

Based on the information above, the ultimate limit state needs to be determined for two ULS:

- Stage 1 (filling): $Q_{stat} + Q_{dyn}$
  - Q_{stat} – silage material load without silage juice
  - Q_{dyn} – compaction machine

- Stage 2 (use period): Q_{stat}
    - Q_{stat} – silage material load with silage juice

Stage 1: (Q_{stat}) silage load without silage juice

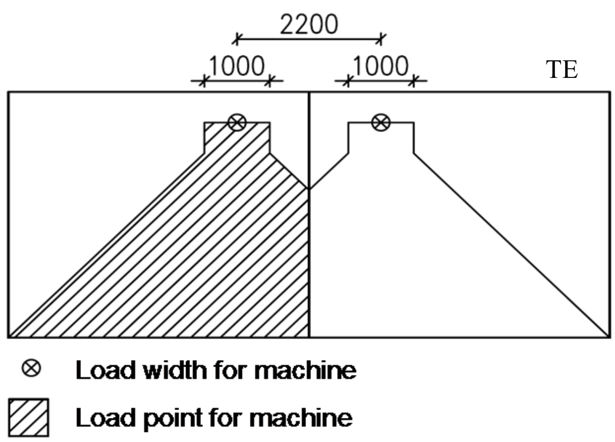
For the calculation of Q_{stat} without silage juice, the load values should be chosen from the area to the right of the 95th percentile trend line, which is in compliance with the equation $Q_{stat} = 4+3x$ (kPa, green triangles), where x = 0 for the bunker silo wall TE.

Stage 1: (Q_{dyn}) compaction machine

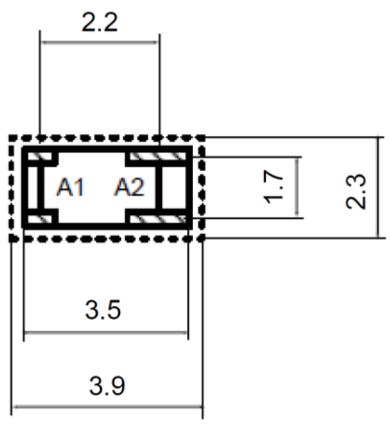
According to JBR (SJV, 1995), the compaction machine has to be considered by applying two point loads comprising 0.1 times the dead weight of the compaction machine, with a wheel base of 2.5 m. The load impact is assumed to act 0.6 m from the silo TE. Our results showed that the influence of the compaction machine is from level z = 0.5 m (Fig. 8). The load arises from the compaction machine. The influence from more than one machine is negligible because the distance between them makes the load decline. The machine closest to the silo wall gives the design load. However, it is difficult to estimate the full influence considering the four wheels of the machine and the number of compaction machines. In the following calculations, a compaction machine of 11 t is used.

The proposed new design guideline load model for compaction machines has the following characteristics:

- A design model based on loads 0.10 m from the bunker silo wall
- Two point loads at 0.15 x dead weight of the compaction machine
- A centre-to-centre distance of 2.2 m between the point loads, i.e. the wheel base (SIS, 2012) (Fig. 8b)
- Point loads acting 0.5 m below TE (Fig. 8a)
- Load distribution width ≥ 1.0 m
- Load distribution through silage from the compaction machine acting on a bunker silo wall according to 1:1 (Fig. 8a)
- Load distribution overlap from the compaction machine not permitted (Fig. 8a).



a)



b)

Fig. 8. Load distribution downwards (mm) in silage matter from the compaction machine with point load acting at 0.5 m below TE (**a**), with given dimensions (m) of the compaction machine (**b**).

Table 6. Calculated bending moment at different levels in ultimate limit stage (ULS) stage 1 and stage 2 and according to Eurocode 0 (Eurocode, 2010) and JBR (SJV, 1995), for a bunker silo wall height of 4 m and a compaction machine of approximately 11 t.

	Calculations based on own measurements applied to Eurocode					Calculations based on JBR	**Max. difference** between using Eurocode and JBR
Level below silage surface	**Stage 1**			**Stage 2**		Design load	
	Silage, characteristic load [a]	Comp. machine, characteristic load	Comp. machine as variable load [c]	Silage incl. silage juice, characteristic load [b]	Silage incl. silage juice as permanent load [d]	Considering silage and comp. machine	
x m	M_{k1} kNm m^{-1}	M_{k2} kNm m^{-1}	M_{d1} c) kNm m^{-1}	M_{k3} kNm m^{-1}	M_{d2} d) kNm m^{-1}	M_{d3} kNm m^{-1}	%
0.00	0.00		0.0	0.0	0.0	0.0	+-0
0.25	0.13		0.1	0.3	0.3	0.3	+2
0.50	0.56	0.00	0.6	1.2	1.3	1.3	+2
0.60	0.83	1.65	3.0	1.7	1.9	1.9	+60
0.75	1.34	4.13	6.7	2.7	3.0	4.4	+50
1.00	2.50	8.25	13.1	4.8	5.4	9.9	+33
1.25	4.10	8.25	14.9	7.7	8.6	13.8	+8
1.35	4.88	8.25	15.8	9.0	10.1	15.0	+5
1.50	6.19	8.25	17.2	11.3	12.6	17.0	+1
1.75	8.80	8.78	20.8	15.6	17.4	20.9	+-0
2.00	12.00	9.52	25.3	20.7	23.2	26.0	-3
2.25	15.82	10.13	30.4	26.6	29.8	32.4	-6
2.50	20.31	10.65	36.1	33.4	37.4	40.6	-8
2.75	25.52	11.08	42.5	41.2	46.1	51.3	-10
3.00	31.50	11.46	49.6	50.0	56.0	64.0	-12
3.25	38.29	11.79	57.6	60.0	67.2	78.8	-15
3.50	45.94	12.07	66.6	71.1	79.7	95.9	-17
3.75	54.49	12.33	76.5	83.5	93.6	115.6	-19
4.00	64.00	12.55	87.4	97.3	109.1	138.1	-21

[a] $q(x) = 4+3x$; [b] $q(x) = 9+2 \times x$ for $x \leq 2$; $q(x) = 13+5(x-2)$ for $2<x\leq 4$

[c] $M_{d1} = 1.35 \times 0.83 \times M_{k1} + 1.5 \times 0.83 \times M_{k2}$

[d] $M_{d2} = 1.35 \times 0.83 \times M_{k3}$

Stage 2: (Q_{stat}) silage load with silage juice

For the calculation of Q_{stat} with silage juice, the load values should be taken from the area to the right of the trend line of the 95th percentile, which is in compliance with the equation $Q_{stat} = 9+2x$ (kPa, green triangles) for $x \leq 2$, i.e. for the upper part of the bunker silo, and $Q_{stat} = 13+5(x-2)$ (kPa) for $2 < x \leq 4$, i.e. for the lower part of the silo.

3.5.4 Ultimate limit state results

In the following, the proposed new design model is compared with JBR (SJV, 1995). Because safety class 1 was chosen, the same material strength is obtained for both JBR and Eurocode, which means that the design loads can be compared (Table 6).

As the comparison of different guidelines in Table 7 shows, JBR gives considerably higher load values than the other guidelines. Above all, there is a rapid increase in the wall load for bunker silos with a wall height of 3 m or more. In addition, few studies have been carried out for silo wall heights higher than 3 m and therefore a conservative approach has been applied. The proposed new guideline values in Fig. 6 (green triangles) coincide with other guidelines in Fig. 1.

Table 7. Comparison between the outcomes of the Eurocode (Eurocode 0, 2010) and JBR guidelines (SJV, 1995) for 2-4 m bunker silo wall height.

Silo height, m	Eurocode, M_d kNm m^{-1}	JBR, M_d kNm m^{-1}	Change, %
2.0	25.3	26.0	-3
3.0	56.0	64.0	-12
4.0	109.1	138.1	-21

4. Discussion

4.1 Silage juice

The silage juice level in the bunker silos differed greatly over time and depended on a number of factors, with DM and pre-drying in the field being key. Other factors such as silo packing at filling, fibre type and silage chopping length were also important, but did not differ significantly between the measuring sites. The silage DM level in the present study was 22-32%, with the majority of measurements in the lower end of the range, which resulted in high silage juice levels.

A close relationship between grass silage juice level and silage DM content, as observed in the present study, has been found in earlier studies (Bastiman, 1976; Sutter, 1955). In the present study, a high silage juice level remained within the silos during storage, which is consistent with findings by O'Donnell (1993) for silos with no drainage system.

In the previous JBR guidelines (SJV, 1995), the highest design juice level after filling was 1.5 m from TE. However in this study, this level was exceeded in 44% of cases for 3 m silo wall height and in 21% of cases for 4 m wall height. In 2011, the silage juice level increased and was redistributed during the first 3 months after filling in 55% of the silos studied. In this respect, the JBR design guidelines, which are based on measurements by Kangro (1986), do not seem relevant, as those measurements do not include silage juice levels after silo filling.

4.2 Static wall load

The static pressure and silage juice level measurements after filling during 2011 showed that the silage juice levels did not reach their peak level until a couple of months after filling. Silage juice was only present at filling in one of 10 cases.

The resulting static load profile at filling (Fig. 5) coincided with the values reported by Kangro (1986), i.e. a linear increase in wall pressure with increasing silo depth. A small deviation occurred in the top layer of the silo, but it had disappeared by the time of the measurements after filling. The higher static load values observed during the measurements after filling were in the same pressure range as reported for maize silage in a silo of similar height in Canada (Zhao & Jofriet, 1991).

The mean silage juice level in the seven silos in which measurements after filling (MAF) were conducted was just above the mean value obtained for all 24 silos in which silage juice was measured. The wall pressure increase due to silage juice pressure in the silos with MAF can thereby be considered representative for the dataset. The pressure increase was only statistically significant for silage juice 3 m from the silo surface, not for the other sensor levels (Table 5). With the bottom sensor, placed only 0.05 m from the silo base, the possibility could not be excluded that this sensor was exposed to a non-measured silage juice pressure from saturated silage. This, together with the fact that the majority of the silage entering the silos had DM lower than 35%, could explain the non-significant result in that case (Tang et al., 1987a). However, the results also reflect the fact that the hydrostatic pressures which may arise when the silage becomes saturated do not act in the same way as free water, as is assumed in the JBR guidelines (SJV, 1995).

4.3 Dynamic wall load

The trend of decreasing dynamic load with increasing distance from TE is in accordance with previous results (Kangro, 1986; Zhao & Jofriet, 1991). In both cases the dynamic load decreased to insignificance at a silo depth of 2 m from TE. In the data presented by Kangro (1986), the weight of the compaction machine was 7.5 tonnes and the tyre width 0.5 m, resulting in a maximum dynamic load of 17 kPa. This corresponds to two point loads of 13.3 kN at 0.5 m below TE. Zhao & Jofriets (1991) used a bulldozer weighing 21 t with 3 m long and 0.5 m wide tracks, which resulted in a maximum dynamic load of 10 kPa at a distance to the silo wall of 0.23 m and at a depth of 0.76 m below TE. With a 5.4-tonne tractor, Messer & Hawkins (1977) recorded a maximum dynamic load at filling corresponding to a point load of 5.9 kN at 0.75 m below TE at a distance to the silo wall of 0.006 m. The magnitude of the maximum dynamic load and its propagation in the present study seems to correspond with that in previous studies.

4.4 New design code

The proposed new load model distinguishes the load variation over time more precisely than before by determining ULS for two stages; filling and the utility period. This means more accurate calculation of the design load. In stage 1, the new design code includes a greater load exerted by the compaction machine at filling and a lower impact of silage and silage juice at the silo wall bottom, especially with increasing silo wall height.

For the compaction machine, the guideline point load of 0.15 × dead weight is based on measured data along with the 95th percentile, which provides more precise criteria for designing the compaction machine load than before. The load distribution width and depth downwards in the silage with given dimensions of the compaction machine also add to the accuracy.

The proposed new design code includes an increased point load value and a wheel base length of 2.2 m (JBR 2.5 m). In ASABE (2008), the point loads may be distributed uniformly on an area no greater than 0.75 m x 0.75 m, considering the maximum wheel load and assuming 75% on the rear axle. In stage 2, the proposed new design code includes the silage material load with silage juice in a more direct way than ASABE (2008), where the standard design loads for bunker silos do not include hydrostatic load, but the mass bulk density of the silage is included as a factor in the silo wall pressure calculation.

5. Summary and conclusions

This study on silo wall design evaluated maximum silage juice levels, while the existing guidelines presumably overestimate the forces arising from silage juice for silos with wall height greater than 3 m.

The silage juice levels were measured by reading the level on measuring sticks in slotted 16-mm pipes placed vertically along the internal silo walls, or in one of the legs of a vertical ladder rack. Measurements in wilted grass and maize were carried out in 24 silos during two seasons, while pressure profiles were measured during 10 cuts of wilted grass and maize harvests in one season, with approximately 400 pressure profiles per cut.

The pressure profile was measured by transducers mounted on the vertical ladder rack, which sent recordings to a data acquisition system displaying static load (pressures imposed by silage material when the compaction machine was not present) and total load (pressure exerted by silage material plus the compaction machine passing in front of the transducer racks). The difference between static load and total load was taken as the dynamic load.

The static silo wall (4 m) pressure was 16 kPa during filling and compaction and 22 kPa at the silo bottom 1-4 months after filling. The hydrostatic pressures occurring when the silage became saturated with silage juice did not act as free water and the silage juice only had an effect after filling and did not interact with compaction. The dynamic load was approximately 17 kPa when the vehicle passed 0.1 m from the silo wall. The horizontal load acting on the silo wall was greatest 0.5-1 m under the silage surface with compaction machine tyre width 0.5 m and machine weight 11.2-14.5 t.

New guidelines are proposed here based on the results obtained and the Eurocode for ultimate limit states (ULS). The data indicated a need to determine the ULS for two stages: 1 (filling): silage material load without silage juice or compaction machine; and 2 (utility period): silage material load with silage juice. The design bending moment for ULS was found to be 21% lower than in the existing JBR guidelines.

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References

ASABE. 2008. Design Loads for Bunker (Horizontal) Silos. ASAE EP538.2 OCT2008.

Bastiman, B. 1976. Factors affecting silage effluent production. Experimental Husbandry, 31, 40-46.

Boverket. 2011. Boverkets föreskrifter och allmänna råd om tillämpning av europeiska konstruktionsstandarder (Eurokoder) (Boverket mandatory provisions and general recommendations on the application of European design standards (Eurocodes)); Boverkets Författningssamling, BFS 2011:10, EKS 8. The Swedish National Board of Housing, Building and Planning.

BSI.1993. BS 5502 – 22: Buildings and structures for agriculture. Code of practice for design, construction and loading. British Standard Institute, London, UK.

Eurocode. 2010. Eurocode 0 – Basis of structural design. EN 1990:2002/A1:2005/AC:2010. European Committee for Standardization. Brussels.

Gruyaert, E., De Belie, N., Matthys, S., Van Nuffel, A. and Sonck, B. 2007. Pressures and deformations of bunker silo walls. Biosystems Engineering 97 (2007) 61-74.

Kangro, A. 1986. Load measurements in bunker silos for silage. Report 48. Swedish University of Agricultural Sciences, department of Agricultural Buildings, Lund.

LBS. 1983. LALT-publikation 2 – Byggnadskonstruktioner (LALT publication 2- Building constructions). Swedish Board of Agriculture, Jönköping.

Martens, P. 1993. Die Neufassung der DIN 11622 – Gärfuttersilos und Gütterbehälter. Proceedings of the Symposium Concrete for a Sustainable Agriculture. BIBM, Cembureau, ERMCO, CIGR. Bologna, Italy 21-23 April 1993.

Messer, H.J.M. and Hawkins, J.C. 1977. The loads exerted by grass silage on bunker silo walls. Journal of Agricultural Engineering Research 22 (4), 327-339.

Minitab. 2007. Minitab Release 15 for Windows, Minitab Inc., State College, PA, USA.

Negi, S. C. and Jofriet, J. C. 1986. Computer-aided prediction of silo-wall pressures. ASAE. Applied Engineering in Agriculture. Vol. 2(2) November 1986. St. Joseph, Michigan.

Nilsson, L. 1982. Laster i ensilagesilor – Genomgång av litteratur och normer. (The loads in horizontal silos – a literature review of silo design codes). Report 23. Swedish University of Agricultural Sciences, Department of Agricultural Buildings, Lund.

O'Donnell, C. 1993. A study of the effects of silage effluent on concrete. Master of English Science Thesis, National University of Ireland.

Savoie, P., Amyot, A. and Thriault, R. 2002. Effect of Moisture Content, Chopping, and Processing on Silage Effluent. Transactions of the ASAE Vol. 45(4): 907-914.

Schemel, H., Fürll, C. and Hoffmann T. 2010. Compression of chopped grass maize and grass in a bunker silo with vibrating rollers. Ag Eng Clermont-Ferrand, France, September 6-8, 2010. ref 015.

SIS. 2012. Ekonomibyggnader - Tillämpningar till Boverkets och Jordbruksverkets regler avseende utformning av ekonomibyggnader för jordbruk, skogsbruk och trädgårdsnäring samt hästverksamhet (Farm building design based on codes from The Swedish National Board of Housing, Building and Planning and The Swedish Board of Agriculture). SIS-TS 37:2012. Swedish Standards Institute Publishers AB. Stockholm.

SJV. 1995. Jordbruksverkets Bygg Råd (JBR) (Swedish Board of Agriculture, Building Advice (JBR). Jönköping.

Stewart, T.A. and McCullough, I.I. 1974. Silage effluent, quantities produced composition and disposal. Agriculture in N. Ireland, 48, 368-374.

Sutter, A. 1955. Problems of waste effluent from silage. Project 307, OEEC, 74-82.

´t Hart, C. 1980. Constructieve richtlijnen voor sleufsilo´s voor de opslag van kuilvoer. (Constructive guidelines for horizontal silos for the storage of silage). PT Bouwkunde, Wegen- en Waterbouw, 35(10), 584-587.

Tang, J., Jofriet, J.C. and LeLievre, B. 1987a. A saturation criterion for ensiled plant material. Canadian Agricultural Engineering, 30, 93-98.

Tang, J., Jofriet, J.C. and LeLievre, B. 1987b. Juice flow from silages. Canadian Agricultural Engineering, 30, 99-106.

Van Nuffel, A., Vangeyte, J., Baert, J., Maertens, W. and Sonck, B. 2008. Is literature on the pressure on farm trench silos walls still accurate? Paper P-105 presented at AgEng 2008 International Conference on Agricultural Engineering, 23-25 June 2008, Hersonissos, Crete, Greece.

Zhao, Q. and Jofriet, J.C. 1991. Structural loads on bunker silo walls: experimental study. Journal of Agricultural Engineering Research 50, 273-290.

Zhao, Q. and Jofriet, J.C. 1992. Structural loads on bunker silo walls: numerical study. Journal of Agricultural Engineering Research 51, 1–13.