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journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Design criteria for structural design of silage silo walls

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ARTICLE INFO

Article history:
Received 22 January 2014
Received in revised form 18 June 2014
Accepted 8 July 2014
Published online 15 August 2014

Keywords:
Bunker silo
Wall
Silage
Pressure
Force

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.

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.

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http://dx.doi.org/10.1016/j.biosystemseng.2014.07.007

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).

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.

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 dry matter (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, Amyot, & Thriault, 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 (Savoie et al., 2002; Schemel, Fürll, & Hoffmann, 2010; Stewart & McCullough, 1974).

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, Jofriet, & LeLievre, 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, Jofriet, & LeLievre, 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 (Gruyaert, De Belie, Matthys, Van Nuffel, & Sonck, 2007; Kangro, 1986; LBS, 1983; Martens, 1993; Negi & Jofriet, 1986; Nilsson, 1982; SJV, 1995; Van Nuffel, Vangeyte, Baert, Maertens, & Sonck, 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.

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