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## **Canadian Building Digest**

Division of Building Research, National Research Council Canada CBD 177

# **Tower Silo Foundations**

Originally published May 1976 M. Bozozuk

## **Please note**

This publication is a part of a discontinued series and is archived here as an historical reference. Readers should consult design and regulatory experts for guidance on the applicability of the information to current construction practice.

Tower silos, tall, bullet-shaped farm structures, are used to store forage crops for feeding cattle. The first tower silos, constructed about 40 years ago, were small, predominantly wooden structures although a few were made of concrete. Since then they have increased in number, size, and capacity, most made of concrete but some of steel. In 1974 more than 3,000 tower silos were erected in Ontario and Quebec, representing an investment of over \$30 million by the agricultural industry in these provinces alone. Some recent structures are fully automated exceed 100 ft (31 m) in height, and have a storage capacity of more than 2500 tons.

Over the years silo builders have improved the design and construction of the above-ground portion of silos but, in contrast, very little has been done to improve the foundation. Towers have generally been erected on foundations prepared by the farmer, who often lacked the necessary technology for adequate design and construction. The practice was reasonably successful when silos were small because the bearing pressures applied to the soils were low. As bigger silos were erected, however, and the applied foundation pressures approached the bearing capacity of the soils, many structures settled considerably, some tilted, and some overturned completely. This Digest outlines the problem and indicates the need for a soil investigation to determine the allowable bearing capacity and compressibility of the soil and thus enable proper foundation design.

#### The Problem

Many tower silos constructed on clay soils have ring-shaped concrete foundations. To reduce costs, concrete floors are seldom provided. When the silos are filled with silage, part of the load is transmitted through the cylindrical walls to the footings and the remainder is carried directly by the soil inside the ring foundation. The underlying clays compress vertically under the weight of the loaded structure in such a way that the applied loads are distributed uniformly to the soil over the whole area enclosed by the circular foundation. This uniform pressure is distributed to the foundation soil in the form of a pressure bulb; its size and shape, determined by elastic theory, are related directly to the diameter of the loaded area as shown in Figure 1. Here, two footings of different size carry the same uniform load, but the pressure bulb under the larger foundation is much larger and deeper. In each case the maximum vertical pressure occurs immediately below the footing and diminishes to 10 per cent of this value at a depth equal to twice the diameter of the soil the structure will be stable.



Figure 1. Pressure bulbs under large and small round foundations.

Non-uniform placement of silage during filling has caused many problems. When the load from the weight of the silage is off centre the pressure bulb will be distorted, as shown in Figure 2(a). Strong winds acting on a tall silo can produce the same effect. The local overstressing of the foundation soil may cause tilting, and unless the problem is remedied it may increase with time until the silo overturns.



Figure 2. Non-uniform and overlapping pressure bulbs.

Pressure bulbs will overlap, as shown in Figure 2(b), if two or more silos are constructed too close to each other. Because pressures are additive, the resulting pressure bulb will be much larger and will extend to greater depths. The soil in the overlap zone will be subjected to higher stresses and the foundations over this region will settle more, causing the silos to tilt towards each other (Figure 3).



*Figure 3. Leaning twin silos caused by non uniform settlement in zone of overlapping pressure bulbs.* 

Most foundation failures (Figure 4) in clay soils occur when a silo is quickly loaded for the first time. As filling proceeds, the loads are applied to the soil skeleton and to the pore water contained within the voids of the clay. Pressures generated in the pore water tend to reduce the friction between soil particles and hence decrease the shear strength of the soil. If, at the end of loading, the available shear strength is greater than the applied shear stresses, the structure will be stable. With time the excess pore water pressures will dissipate, the soils will consolidate and gain strength, and the structure will be stable for subsequent loadings.



Figure 4. Failure of a 2500-ton capacity silo damaging adjacent barns.

In silos without floors, silage juices normally seep into the underlying soil. Pore pressures are increased even more, causing a further decrease in the shear strength of the soil. The footings may also become undermined when the juices flow through the soil under hydraulic pressure. Either or both of these actions can trigger a bearing capacity failure.

#### **Bearing Capacity of Clay**

When a silo overturns the foundation soil rotates along a circular arc (Figure 5). The direction of the applied shear stress along the slip circle changes from 0 to 90 deg from the vertical. In rare cases the shear strength of the soil is isotropic (constant in all directions), but generally it is anisotropic (varies with the direction of applied shear stress). Investigations of marine clays have shown orientation dependent reduction in shear strength of as much as 35 per cent when compared with the strength measured in the vertical direction. It is imperative, therefore, that an adequate factor of safety should be included to allow for strength anisotropy, non-uniform pressures applied to the soil due to eccentric loads and overturning moments from high winds, and to prevent excessive vertical settlements. This factor of safety is applied to the shear strength of the soil in the following equation:

$$q_a = \frac{C}{-N_c + P}$$

where  $q_a =$  allowable bearing capacity

- C = Average shear strength of soil to a depth below the footings equal to 2/3 the outer diameter of the foundation
- $N_c$  = shape factor = 6.6 for a circular foundation
- P = YD = overburden pressure at footing level where D = depth of footing and Y = density of soil
- F = factor of safety against a bearing capacity failure (generally = 3).



Figure 5. Attitude of a silo foundation after failure.

#### Soil Investigations Needed

Bearing capacity and vertical settlement are directly related to the engineering properties of the soil at a site, so that a soil investigation is required to provide information on soil profile, location of the groundwater table, index properties, shear strength, and compressibility. Previous Digests (CBD 29, CBD 43) provide more detailed information on engineering site investigations and soil testing.

To determine the bearing capacity of soil, shear strength measurements are required to a depth below the footings equal to two thirds the diameter of the foundation. The number of tests required as a function of depth should be sufficient to determine the strength of the various strata within this depth.

Shear strength may be measured by several methods: in the field, in situ, by means of a field vane or cone penetrometer pushed vertically into the soil to obtain the strength of specific layers at different depths; in the laboratory, by unconfined compression or triaxial strength tests performed on undisturbed samples of soil.

To estimate vertical settlement of the structure consolidation tests are required to a depth equal to twice the diameter of the foundation. These tests should be performed on representative undisturbed soil samples obtained from each of the major soil formations.

It cannot be emphasized too strongly that extensive soil investigations are necessary to assure a good foundation design for silos constructed on clays. Normally, such investigations are carried out by a soils engineering consultant.

#### **Precautions in Designing Foundations for Silos**

Every owner should insist on an adequate foundation for his silo (CBD 80, **CBD 81**). The following points should be considered to ensure a stable structure:

#### Reinforced Footings

A ring foundation is subject to bending stresses from vertical wall loads, soil pressures, and the circumferential loads that exist in the walls at the base of the silo. As concrete has a low tensile strength, the foundation should be reinforced with steel to resist such bending moments and tensile stresses. If the foundation should crack because of insufficient reinforcement, the monolithic behaviour of the ring foundation will be destroyed and its ability to support the superstructure adequately will be reduced.

#### Concrete Foundation

It is most important to use good quality concrete in a well prepared excavation in which the sides are neatly trimmed and the floor cleaned of all disturbed soil. In granular soils or soils containing boulders, formwork may be necessary. The concrete must be placed with the same care as would be followed in constructing the silo walls. To employ no quality control on either concrete or workmanship is unacceptable!

#### Centring Silo on Footings

Load-bearing walls should be centred on footings whenever possible in order to apply uniform loads to the foundation soil and thus permit full use of its allowable bearing capacity.

Large foundations are required in soft, weak soils to maintain applied pressures within the allowable bearing capacity. Large-diameter ring foundations projecting beyond the silo walls are often used to provide maximum stability against overturning. The interior floor is usually omitted for reasons of economy. The inner diameter of this foundation is normally slightly less than the inner diameter of the silo wall. Because the heavy wall loads applied to the inner edge tend to deform the ring foundation it could easily break into individual sections unless it is properly reinforced. In this case the footing pressures would not be uniform and local overstressing of the underlying soil could occur. With adequate reinforcing, however, and by extending the footing further inside the silo, the contact pressures would be redistributed more uniformly and any tendency of the foundation to deform would be reduced. The additional

weight of the silage on the extended footing would be minimal because most of the silage load is transferred to the silo walls through friction.

#### Silo Groups

To avoid any interaction between silos constructed on compressible clays loaded to the allowable bearing capacity it is recommended that the minimum horizontal clearance between them should be not less than the diameter of the ring foundations. If a smaller spacing is desired, the silos should be constructed on piles or on a common mat foundation adequately reinforced to resist the applied bending moments.

#### Silage Juices

Large quantities of silage juices form when forage crops are stored wet, i.e., when their moisture content is too great. In tower silos constructed without floors, the juices can flow under high hydrostatic pressure into the foundation soil and undermine the foundations. They can increase the pore water pressures in saturated clay soils, reducing the shear strength. In addition, chemical reaction with the soil may further decrease soil strength.

An impermeable floor should be installed to prevent juices from penetrating the subsoil, and drains should be provided to carry them away and reduce the hydrostatic pressures in the silo. It is important that the drains continue to function for the life of the structure.

#### **Concluding Remarks**

The agricultural industry should be aware of the many aspects of design and construction of tower silos on clay soils. A contractor's experience may be sufficient for building average size structures, but for very large tower silos there should be a thorough soil investigation carried out under professional guidance. It is not possible to build an economical and safe foundation unless the properties of the foundation soils are known and considered in the design. Furthermore, quality control and on-site inspection is required during construction.

Performance requirements for tower silos also have to be established. For example, how much vertical settlement or tilting can be allowed without the performance of the structure being affected? Is there an optimum limit for the ratio of height to diameter of the silo? Answers to these and other questions can be obtained by studying the performance of existing silos and from the instrumentation of new structures on different soils in Canada.