# Design recommendations for structural loads on horizontal silo walls

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Jofriet, J.C., Zhao, Q. and Negi, S.C. 1992. **Design recommendations for structural loads on horizontal silo walls**. Can. Agric. Eng. 34:095-104. Design loads on the walls of horizontal (bunker) silos are affected by wall slope, silage-wall friction, the way in which the silage is piled up above the top of the wall and the compaction method. Most of these factors are not accounted for in the present Canadian Farm Building Code. Structural problems have been experienced with some very high walls. Based on a three-year study of horizontal silo wall loads, this paper presents simple design formulae which take into account the various factors mentioned earlier. Design wall loading from silage is proposed as an equivalent liquid pressure using a pressure ratio K that is closely related to the "at rest" pressure ratio. For corn silage it is recommended that the value of K be taken as $1.65K_A$, where $K_A$, the active pressure ratio, is based on an internal angle of friction of 29°. The dry matter density, in kg/m$^3$, is recommended to be 200 plus 4 times the mass, in tonnes, of the vehicle used for compaction of the silage. Based on a six year study carried out by Messer and Hawkins in England it is believed that the same design recommendation is valid for grass. It is also proposed that the design load from a tracked compaction vehicle is a line load equal to $K_f$ times the line load representing one track. This design load is applied anywhere at right angles to the wall surface, 0.5 m below the silage surface, in the most unfavourable location. Similarly, the design load from a wheeled tractor is a point load equal to $K_f$ times the wheel load. For all design loads $K_f$ can be taken as $1.65K_A$ where $K_A$ is based, for corn silage, on an internal angle of friction of 29°.

Les charges nominales exercées sur les parois de silos horizontaux (bunkers) dépendent de l'inclinaison des parois, du frottement ensilage-paroi, de la manière dont l'ensilage est empilé au-dessus du sommet des parois et de la méthode de compactage, mais l'actuel Code de construction des bâtiments agricoles ne tient pas compte de la plupart de ces facteurs. De plus, quelques parois très hautes ont présenté des problèmes structuraux. Rédigée à partir d'une étude de trois ans relative à des charges exercées sur des parois de silos horizontaux, cette communication présente des formules de conception simples, qui tiennent compte des différents facteurs mentionnés ci-dessus. La charge nominale exercée par l'ensilage sur les parois est proposée comme une pression liquide équivalente, en utilisant un taux de compression K étroitement relié au taux de compression «au repos». Pour l'ensilage de maïs, il est recommandé que la valeur de K soit de $1,65K_A$, et que K, le taux de compression effective, soit basé sur un angle de frottement interne de 29°. On recommande que la masse volumique sèche, en kg/m$^3$, soit de 200 plus 4 fois la masse en tonnes du véhicule utilisé pour le compactage de l'ensilage. À la suite d'une étude de six ans menée par Messer et Hawkins en Angleterre, on pense que les mêmes recommandations de calculs sont valables pour l'herbe. On recommande également que la charge nominale d'un véhicule de compactage à chenille soit une charge linéaire équivalant à $K_f$ fois la charge linéaire d'une chenille. Cette charge nominale s'applique n'importe où à angles droits à la surface des murs, à 0,5 m sous la surface de l'ensilage à l'endroit le plus défavorable. De même, la charge nominale d'un tracteur à roues est une charge ponctuelle équivalant à $K_f$ fois la charge des roues. Pour toutes les charges nominales, $K_f$ peut être considéré comme étant équivalent à $1,65K_A$, $K_A$ étant basé, pour l'ensilage du maïs, sur un angle de frottement interne de 29°.

## INTRODUCTION

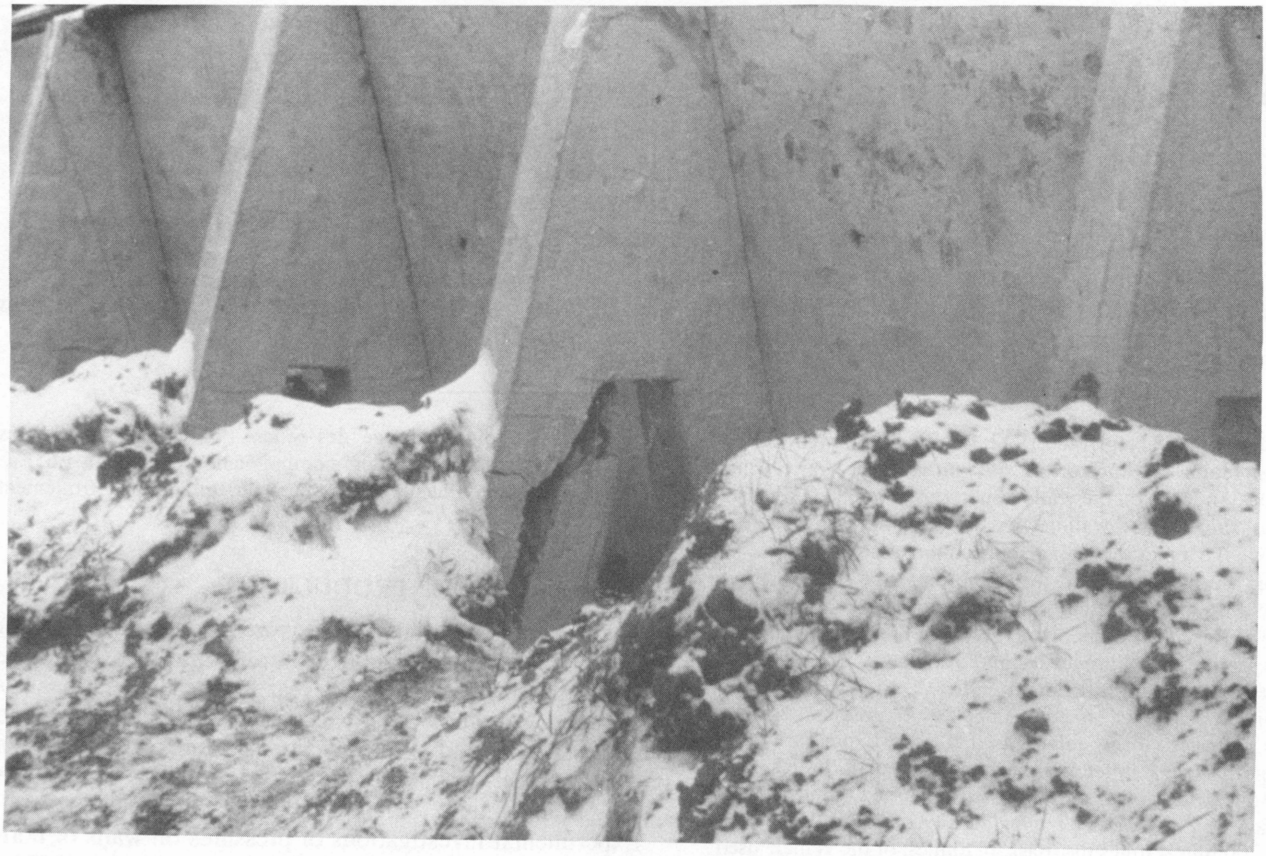
In Canada, horizontal (bunker) silos are used to store silage for livestock on large dairy and beef farms or ranches. The large amount of feed required over a year for these operations has led to the construction of large capacity silos with walls up to 6 m high. The design of these major structures has often been based on research with small horizontal silos with walls of less than 2.5 m height.

Experimental investigations of pressures on walls of horizontal silos can be traced back to the early 1950's. Experiments were conducted with grass silage on wooden as well as concrete silos. Those early investigations were limited to small silos with walls less than 2.5 m high (Esmay and Brooker 1955; Esmay et al. 1956; Young 1957; Hendrix and McCalmont 1958; Zoerb et al. 1959). Design loads for horizontal silo walls in North America have for many years been based on the results of experiments conducted on these small silos. For example, the 1983 Canadian Farm Building Code (NRC 1983) specified a constant design wall load of 6.7 kPa from a depth of 0.6 m below the silage surface down to the floor, regardless of height of the wall.

Messer and Hawkins (1977a) investigated several on-farm horizontal silos with walls over 4 m high. They measured pressures and densities of grass silages in horizontal silos over a period of about six years. The silage was compacted with tractors of a mass ranging from 2.6 to 7.0 t. The lateral wall pressure was reported in the form of an equivalent liquid pressure. Messer and Hawkins (1977b, 1977c) also carried out research with small (about 10 t capacity) experimental silos over a number of years. The silage in these experiments was compacted by a man walking over the silage which was deposited in 600 mm layers. They found little difference between pressures from corn and grass silage.

More recent measurements of silage pressures on horizontal silo walls were conducted in Sweden by Kangro (1986). Based on his experimental results, he too recommended a wall pressure that increases linearly with depth.

In 1986, a failure was reported in the support buttress of a precast concrete 6.1 m high horizontal silo in Alberta, Canada (Fig. 1). Severe cracks were found in the support buttresses and in the concrete wall panels of three silos with equally high



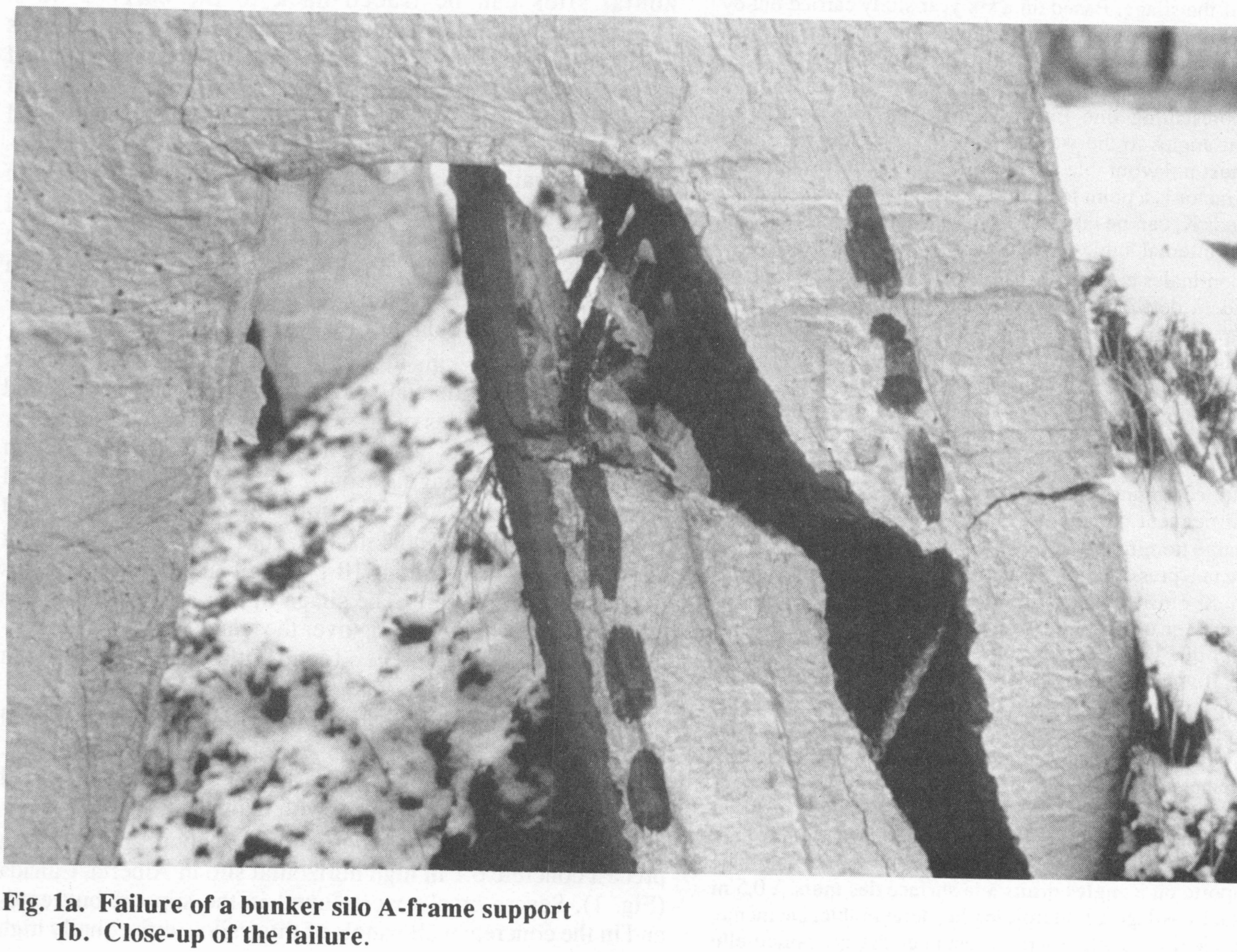


**Fig. 1a. Failure of a bunker silo A-frame support**
**1b. Close-up of the failure.**

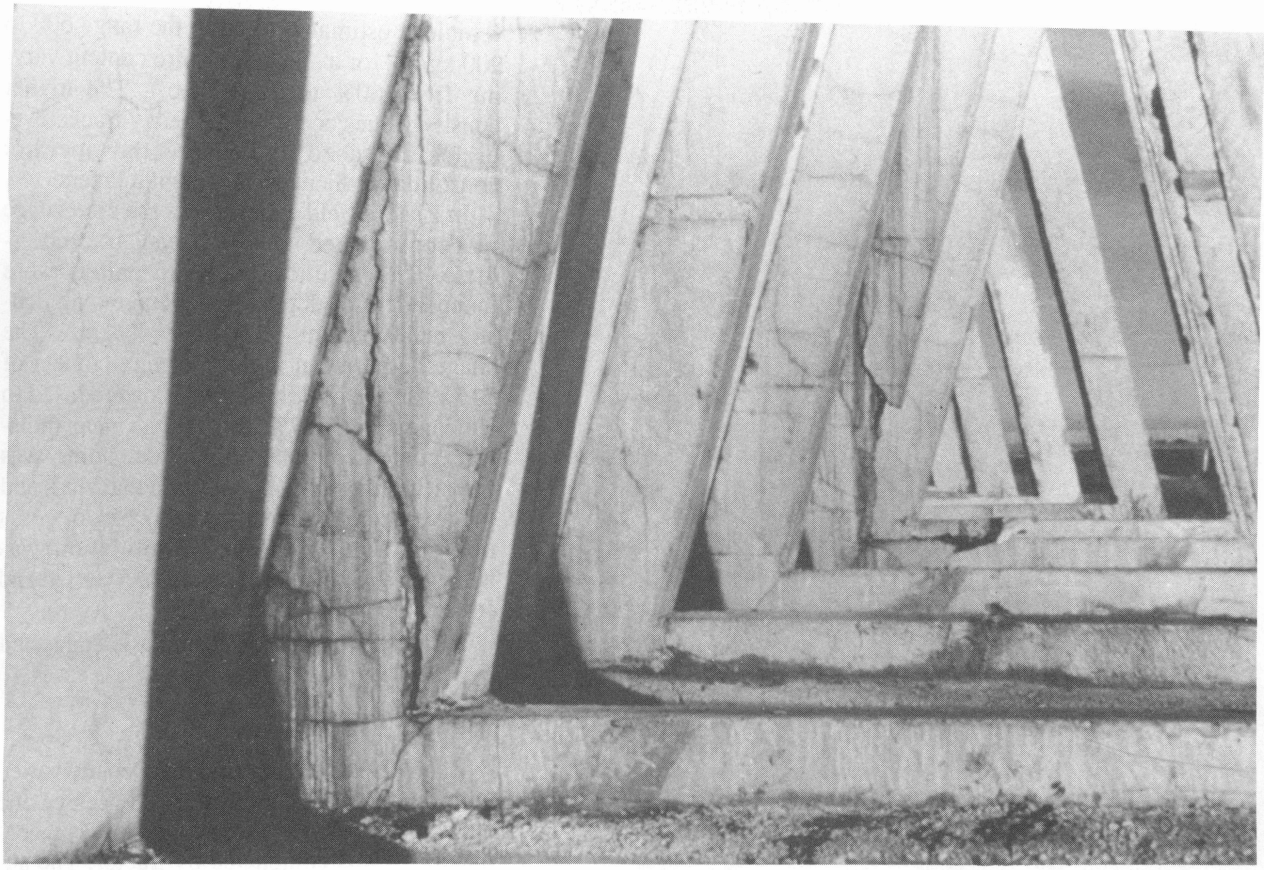


**Fig. 2a. Severe cracking of a bunker silo A-frame support.**

walls (Fig. 2). More recently, cracks have been observed in a number of precast concrete buttresses of a 51 x 90 m horizontal silo with 4.8 m high walls in Walkerton, ON.

As noted by Turnbull et al. (1987) and Jofriet et al. (1988), the 1983 CFBC design pressures for horizontal silos were quite unsafe for walls over 2 m high. A two-year full-scale field experiment on a horizontal silo with 4.83 m high walls (Zhao 1990) has confirmed the conclusions by Turnbull et al. (1987) and Jofriet et al. (1988).

The recently published 1990 Canadian Farm Building Code (NRC 1990) specifies a wall load for horizontal silos as (Fig. 3):

$$p = 3.5 + 3.5z \quad (1)$$

The design load from the compaction equipment in the 1990 CFBC is the greater of 30% of the maximum wheel load or 10% of the tractor total weight but not less than 5 kN. This load is applied normal to the wall to an area 0.6 $m^2$ centered 0.6 m below the silage surface and located to produce the most critical design condition.

The British code BS 5502 (BSI 1987) specifies the design loads for horizontal silos as (Fig. 3):

$$p = 3.9 + 3.9z \quad \text{for } M \leq 8 \text{ t} \quad (2)$$

$$p = 4.5 + 4.5z \quad \text{for } 8 \text{ t} \leq M \leq 10 \text{ t} \quad (3)$$

The two concentrated loads due to compaction equipment are specified to be 4 kN for a wheeled tractor with a gross mass not exceeding 8 t and 5 kN for a wheeled tractor with a gross mass between 8 t and 10 t. These concentrated wall loads from compaction equipment act horizontally on an area 0.6 m by 0.6 m, centered 0.6 m below the surface of the silage and 2 m apart along the wall. The British code also points out that when compaction is carried out with machinery exceeding 10 t or when the wheels of a vehicle come into contact with the wall face, loadings become extremely high and special consideration should be given to the design of the walls. The code, however, does not quantify the extremely high loadings.

Neither NRC (1990) nor BSI (1987) gives any information on the effects of the friction between silage and wall surface, and of the way the silage is piled up above the top of the wall. BSI (1987) does not consider the influence of wall slope either. Information on wall loads from compaction is also very incomplete.

Simple design guidelines are needed for practical designs of horizontal silos. Yet, design loads must be sufficiently comprehensive to provide safe structures. This paper presents the authors' design recommendations for horizontal silos for corn silage, based on the results of a comprehensive three-year study of horizontal silo wall loads (Zhao 1990). Simple formulae will be proposed for calculating wall design loadings from both silage and the compaction vehicles. The authors will also propose that, based on a large research project carried out by Messer and Hawkins (1977a, 1977b, 1977c), the design recommendations are suitable for grass silage as well.

## WALL LOADINGS DUE TO SILAGE

The study by Zhao (1990) and the various studies by Messer and Hawkins (1977a, 1977b, 1977c) showed clearly that the wall normal pressure from silage weight increases approxi-

**Fig. 2b. Severe cracking of a bunker silo A-frame support.**

vehicle is estimated to be in the range 600 to 900 kg/m$^3$ for a silage moisture content varying from 60% to 70% (w.b.). The higher density values occur where heavy tracked vehicles are used and where the operator consolidates the material in small layers.

In Zhao's field experiments the corn silage was consolidated with a 21 tonne tracked vehicle. The resulting silage densities were independent of depth. The average bulk density measured in 1987 was 874 kg/m$^3$. The silage had a mean initial moisture content of 71%. At time of unloading this had reduced to a mean value of 67%. In 1988 the mean moisture content at loading and unloading was 66% (the silage was not covered that year) and the average bulk density was 822 kg/m$^3$. It is obvious that excellent consolidation was achieved by this farm operator (Darby and Jofriet 1991).

A density prediction formula is suggested by BSI (1987) as:

$$\rho = 400 + 72z \tag{5}$$

Zhao (1990) did not find that density varied with depth significantly, nor did Messer and Hawkins (1977a) in those field studies where the silage was compacted by tractor. The authors do not feel that the bulk density should be expressed in terms of depth as in BSI (1987). Moisture content of the silage and the weight of the compaction equipment are more important parameters. More experiments are required to correlate the silage bulk density in horizontal silos with the compaction load and the moisture content of silage. Subject to further field testing the authors recommend for design:

$$\rho_d = 200 + 4M \tag{6}$$

The dry matter density determined with Eq. 6 is 284 kg/m$^3$ given a 21 t gross mass of the compaction equipment. This means a bulk density of about 810 kg/m$^3$ for 65% moisture content corn silage; for a moisture content of 67% the bulk density would be about 860 kg/m$^3$. For corn silage compacted with a 10 tonne vehicle Eq. 6 would give bulk densities of about 685 and 725 kg/m$^3$ corresponding to moisture contents of 65 and 67%.

mately linearly with vertical depth from the top of the silage at the wall. This wall loading can be expressed in the form of the Coulomb equation used extensively for the design of earth retaining structures. The normal wall loading can be expressed as an equivalent liquid pressure:

$$p = Kq = K\rho g z \tag{4}$$

Equation 4 is the authors' recommended design formula for computing the normal wall load due to silage pressure. Recommendations for the appropriate values for the bulk density, $\rho$, and the pressure ratio, $K$, follow.

### Recommended bulk density of silage

The silage bulk density, $\rho$, is a function mainly of the compaction method and the silage moisture content at time of compaction. The density range of whole-plant corn silage in horizontal silos compacted by either a wheeled or a tracked

### Recommended silage pressure ratio

The ratio of horizontal to vertical stress in a particulate solid is defined as the pressure ratio. The three states of stress associated with the pressure ratio are referred to as the active, passive and at rest states. The first two are the result of wall movement, respectively away and toward the stored material, while the third occurs when the material is prevented from lateral strain by an unyielding retaining structure.

The walls of most horizontal silo structures are relatively rigid when compared to the material properties of the stored

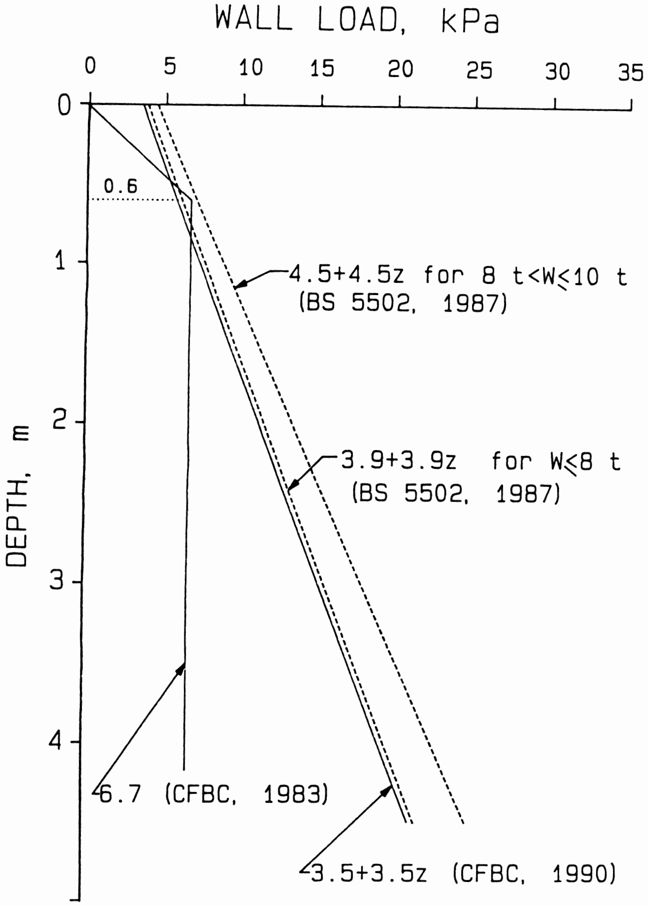



**Fig. 3. CFBC and BS 5502 horizontal silo design wall loads.**

silage. It is therefore not reasonable to presume that the silage is at a failure state. Thus the active wall pressures are not appropriate and the more conservative "at rest" state of stress must be assumed and the "at rest" pressure ratio $K_o$ must be considered in Eq. 4. Jaky (1944) related $K_o$ to the internal angle of friction, $\phi'$:

$$K_o = 1 - \sin \phi' \tag{7}$$

A review of laboratory test results of over 170 different soils by Mayne and Kulhawy (1982) has showed that Jaky's simple relationship is valid for normally consolidated soils. Zhao (1990) concluded from two years of field testing and from laboratory bench tests that for whole plant corn silage an appropriate value for $K_o$ is about 0.52. Substitution of this value in Jaky's equation (Eq. 7) would provide an internal angle of friction of 29°. Le Lievre and Jofriet (1982) found that $\phi'$ of haylage is dependent on fibre orientation. They suggested a value of 32°, virtually equal to that found from Eq. 7 and the $K_o$ value of 0.52. An angle of 29° is used in subsequent analyses.

The "at rest" pressure ratio can be used directly for the determination of wall loads where there is no friction between silage and wall, where the wall is vertical, and where the top of the silage pile is level. This condition, of course, does not occur in practical situations. There is little information on the effect on $K_o$ of wall slope and the slope of the top of the retained material. Wall friction must also be taken into account.

Zhao (1990) found from a comprehensive numerical study that the pressure ratio $K$, the ratio of lateral to vertical pressure, decreases with increase in wall-silage friction coefficient in the same ratio as does the active pressure ratio, $K_A$. The effect of wall slope and friction on $K_A$ was expressed by Terzaghi (1943) as:

$$K_A = \left[ \frac{\sin(\delta + \phi')\csc(\delta)}{\sqrt{\sin(\delta - \phi)} + \dfrac{\sqrt{\sin(\phi' + \phi)\sin(\phi' - \alpha)}}{\sqrt{\sin(\delta + \alpha)}}} \right]^2 \tag{8}$$

Figure 4 shows the various angles in Eq. 8. Table I provides values of $K$ determined by Zhao (1990) together with parallel values of $K_A$ calculated from Eq. 8. It is evident that the ratio between the two is almost independent of $\phi$. The average ratio is 1.5.

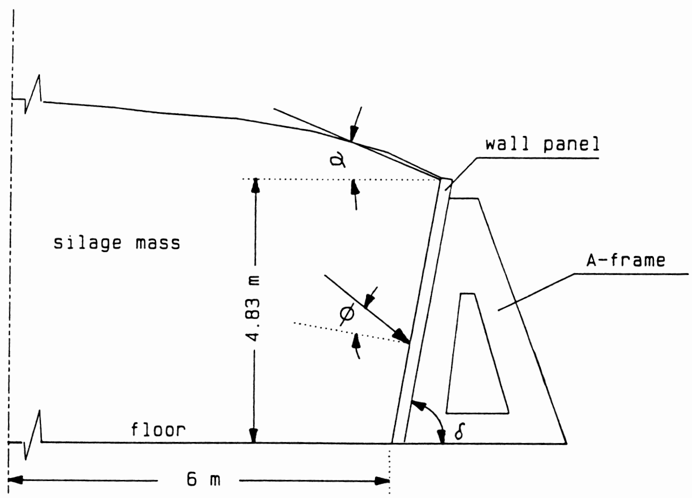



**Fig. 4. Schematic cross section of a horizontal silo wall showing the various angles used in calculating the pressure ratio.**

**Table I. Pressure ratios as a function of wall friction, $\phi$, with $\beta$= 0°, $\alpha$= 0° and $\phi'$ = 29°**

| $\phi$ | 0.0° | 2.86° | 5.71° | 11.31° | 16.7° | 21.8° |
|---|---|---|---|---|---|---|
| $K_A$ | 0.347 | 0.338 | 0.330 | 0.318 | 0.311 | 0.308 |
| $K$ | 0.515 | 0.507 | 0.498 | 0.482 | 0.466 | 0.452 |
| $K/K_A$ | 1.48 | 1.50 | 1.51 | 1.51 | 1.50 | 1.47 |

$\beta$= wall slope with the vertical = 90° - $\delta$

**Table II. Pressure ratios as a function of wall slope, $\beta$, with $\phi$ = 0°, $\alpha$= 0° and $\phi'$ = 29°**

| $\beta$ | 0° | 5° | 10° | 15° |
|---|---|---|---|---|
| $K_A$ | 0.347 | 0.382 | 0.420 | 0.463 |
| $K$ | 0.515 | 0.595 | 0.672 | 0.746 |
| $K/K_A$ | 1.48 | 1.56 | 1.60 | 1.61 |

The pressure ratio, $K$, also increases with increasing wall slope, $\beta$. Table II shows Zhao's values for $K$ together with values of $K_A$ and the ratio $K/K_A$. Again the ratio is almost independent of the wall slope, $\beta$, in the practical range of $0^o$ to $15^o$. The average value of the ratio $K/K_A$ is 1.56.

The effect of the surcharge angle, $\alpha$, the slope of the top of the silage, is illustrated in Table III which shows $K$, $K_A$ and the ratio $K/K_A$ for values of $\alpha$ ranging from $0^o$ to $20^o$. The ratio $K/K_A$ ranges from 1.48 to 1.82 as the surcharge angle $\alpha$ increases from $0^o$ to $20^o$; the mean value is 1.67.

The practical range of values for the parameters that affect the pressure ratio is smaller than that presented in Tables I, II and III. The wall friction coefficient is not likely to be less than 0.3 ( $\phi = 16.7^o$) for concrete. The most commonly used wall slope is $10^o$ and the slope with which the silage is banked up is commonly less than $10^o$, and rarely greater than $15^o$ (about 1 in 4 slope). Using that limited range for the parameters, a reasonable design value for $K$ in Eq. 4 for corn silage can be determined from:

$$K = 1.65K_A \qquad (\phi = 29^o) \tag{9}$$

**Table III. Pressure ratios as a function of surcharge angle, $\alpha$, with $\phi = 0^o$, $\beta = 0^o$ and $\phi' = 29^o$**

| $\alpha$ | $0^o$ | $5^o$ | $10^o$ | $15^o$ | $20^o$ |
|---|---|---|---|---|---|
| $K_A$ | 0.347 | 0.366 | 0.390 | 0.421 | 0.464 |
| $K$ | 0.515 | 0.582 | 0.659 | 0.746 | 0.844 |
| $K/K_A$ | 1.48 | 1.59 | 1.69 | 1.77 | 1.82 |

**Table IV. Pressure ratio calculated with Eqs. 8 and 9; wall-silage friction angle $\phi = 16.7^o$; friction coefficient= 0.3**

| Wall angle $\beta$ (degrees) | Surcharge angle of silage, $\alpha$ (degrees) | Pressure ratio $K$ Eq. 9 (1) | FEM (2) | Eq.9/FEM (3) |
|---|---|---|---|---|
| | 0 | 0.514 | 0.466 | 1.10 |
| | 5 | 0.547 | 0.531 | 1.03 |
| 0 | 10 | 0.588 | 0.607 | 0.97 |
| | 15 | 0.642 | 0.693 | 0.93 |
| | 20 | 0.720 | 0.789 | 0.91 |
| | 0 | 0.575 | 0.537 | 1.07 |
| | 5 | 0.614 | 0.609 | 1.01 |
| 5 | 10 | 0.662 | 0.692 | 0.96 |
| | 15 | 0.725 | 0.788 | 0.92 |
| | 20 | 0.816 | 0.889 | 0.92 |
| | 0 | 0.642 | 0.605 | 1.06 |
| | 5 | 0.689 | 0.685 | 1.01 |
| 10 | 10 | 0.746 | 0.775 | 0.96 |
| | 15 | 0.820 | 0.877 | 0.93 |
| | 20 | 0.925 | 0.990 | 0.93 |
| | 0 | 0.719 | 0.669 | 1.07 |
| | 5 | 0.775 | 0.762 | 1.02 |
| 15 | 10 | 0.842 | 0.855 | 0.99 |
| | 15 | 0.929 | 0.966 | 0.96 |
| | 20 | 1.053 | 1.088 | 0.97 |

**Table V. Pressure ratio calculated with Eqs. 8 and 9; wall-silage friction angle $\phi = 21.8^o$; friction coefficient= 0.4**

| Wall angle $\beta$ (degrees) | Surcharge angle of silage, $\alpha$ (degrees) | Pressure ratio K Eq. 9 (1) | FEM (2) | Eq. 9/FEM (3) |
|---|---|---|---|---|
| | 0 | 0.508 | 0.452 | 1.12 |
| | 5 | 0.542 | 0.516 | 1.05 |
| 0 | 10 | 0.584 | 0.591 | 0.99 |
| | 15 | 0.640 | 0.676 | 0.95 |
| | 20 | 0.721 | 0.771 | 0.94 |
| | 0 | 0.571 | 0.519 | 1.10 |
| | 5 | 0.612 | 0.591 | 1.03 |
| 5 | 10 | 0.662 | 0.673 | 0.98 |
| | 15 | 0.727 | 0.766 | 0.95 |
| | 20 | 0.822 | 0.869 | 0.95 |
| | 0 | 0.642 | 0.584 | 1.10 |
| | 5 | 0.690 | 0.663 | 1.04 |
| 10 | 10 | 0.750 | 0.754 | 0.99 |
| | 15 | 0.828 | 0.855 | 0.97 |
| | 20 | 0.939 | 0.968 | 0.97 |
| | 0 | 0.722 | 0.646 | 1.12 |
| | 5 | 0.780 | 0.744 | 1.05 |
| 15 | 10 | 0.852 | 0.831 | 1.03 |
| | 15 | 0.944 | 0.941 | 1.00 |
| | 20 | 1.076 | 1.063 | 1.01 |

Tables IV and V list values for $K$ determined with Eq. 9 and those from Zhao's study (1990). The ratio of the $K$ values calculated with Eq. 9 to Zhao's (1990) values is shown in the last column of Tables IV and V. Table IV illustrates the values for a wall-silage friction angle of $16.7^o$; this corresponds to a coefficient of friction of 0.3. Table V has the values for a coefficient of friction of 0.4.

The ratio of the suggested design values for $K$ (Eq. 9) to the values by Zhao (1990) from finite element analysis solutions ranges from 1.10 to 0.91 for a wall friction coefficient of 0.3; for a friction coefficient of 0.4 the range is 1.12 to 0.94. This indicates a good level of agreement.

Friction between the concrete wall surface and the silage tends to reduce the loading normal to the wall. For conservative designs the silage-wall friction should be estimated low when calculating the normal wall pressures due to silage. For instance, the lowest value in the range for $\phi$ given in NRC (1990), e.g. 0.4 for whole-plant silage against a concrete wall, should be selected. The recommendation in BSI (1987) that the silage-wall friction be ignored is considered to be too conservative.

It is of interest to compare the suggested design procedure with the design formula in NRC (1990). Assuming a wall slope of 10°, a wall friction coefficient of 0.4 and assuming that the top of the silage is flush with the top of a 5 m high wall the $K$ from Eq. 9 would be 0.642 (see Table V). If it is further assumed that the corn silage has an average density of 750 kg/m$^3$, the pressure at the bottom of the wall would be, from Eq. 4, 23.6 kPa. NRC (1990), using Eq. 1, would provide a pressure of 21.0 kPa. Thus the code provides a reasonable design value in this case. However, if the silage is piled up at an angle of say 10°, as is so often the case, $K$ would be 0.750 and the pressure at the bottom would be 27.6 kPa. This is 31% greater than the code value.

The tests upon which the above analyses are based were carried out with corn silage. Messer and Hawkins (1977b, 1977c) found little difference between grass and corn silage pressures. They did note that grass can be compacted more easily than corn silage. An analysis of the Messer and Hawkins (1977a) results from full-scale silo tests with grass silage compacted by tractor showed values of $K$ that vary from 0.35 to 0.96, assuming linearly increasing pressures. The mean for vertical walls was 0.55, the one that sloped 3° indicated a $K$ of 0.66 and the mean for the two walls with a slope of 6° was 0.59. The material of the surface of the pressure panels in contact with the silage is not known. However, assuming a low coefficient of friction of 0.3, the values obtained from Eq. 9, $K$ = 0.514 for a wall slope of 0° and 0.575 for 5°, would be quite acceptable for design of bunker silos with grass silage. The authors feel that Eq. 9 can be used for all whole-plant silages.

The suggested design procedure allows the designer to cope with a variety of field conditions that the present code can not. The procedure is identical to that used for the design of retaining walls in civil engineering practice. National Standard CAN/CSA-S6-88 (CSA 1988) has a provision for determining pressures on retaining walls backfilled with free-draining granular material using the equivalent fluid pressure method. It specifies a ratio of at-rest condition to active state of 1.5 for ultimate limit state design and 1.54 for serviceability limit states. The internal angle of friction is assumed to be 30°.

## WALL LOADING DUE TO COMPACTION VEHICLES

The study by Zhao (1990) included a comprehensive study of wall pressures resulting from the compaction equipment operating on top of the silage. Both field experiments and analyses were used in the study. The conclusions were:

1. The maximum normal wall pressure on a wall that slopes 10° due to the weight of a tracked compaction vehicle can be as high as 40% of the pressure under the tracks.
2. The effect of tracked compaction vehicle on the wall extends to a horizontal length equal to the length of the tracks; it can be approximated by a line load of the same length, acting normal to the wall.
3. About 50% of the wheel load of a wheeled compaction vehicle is imposed normal to a wall that has a 10° slope; the pressure diagram has a prismatic shape acting on an area about 1 m x 1 m in size.
4. Any point or line load acting more than 2 m from the wall has little effect on the wall pressures.
5. The maximum wall pressure due to compaction increases with wall slope.

Design recommendations will be derived separately for tracked compaction equipment and for wheeled tractors.

### Load due to compaction by tracked vehicles

The normal wall pressures due to the weight of a 21 tonne tracked vehicle on top of the silage are shown versus vertical depth in Fig. 5 and versus horizontal distance from the centre of the track in Fig. 6. The total vertical force on the track, which has a contact area of 3.0 m by 0.5 m is 103 kN. This can be represented by a vertical line load on the surface of the silage which can be computed as:

$$L' = (103\ \text{kN})/(3.0\ \text{m}) = 34.3\ \text{kN/m}$$

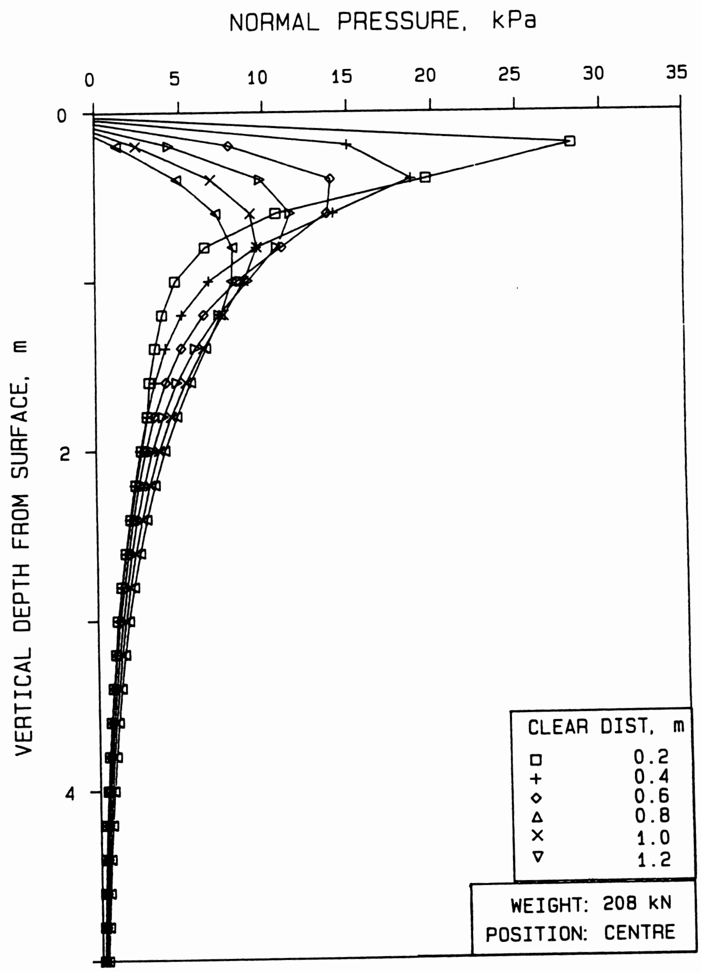



**Fig. 5. Normal pressures versus depth at the centre due to 21 tonne tracked vehicle positioned 0.2, 0.4, 0.6, 0.8,1.0 and 1.2 m from the wall.**

The maximum wall pressure for a clear distance between the track and the wall of 0.2 m is 27.5 kPa, 40% of the pressure under the tracks of the tracked vehicle. The prismatic pressure diagram can be integrated to a resultant line load (Fig. 5). The area can be simplified to a triangular load with a maximum value of 27.5 kPa and a base of about 1.1 m, so:

$$L = (27.5\ \text{kPa})\text{x}(1.1\ \text{m}/2) = 15.1\ \text{kN/m}$$

This wall line load acts on a length equal to that of the track (3.0 m) about 0.5 m below the silage surface. The ratio of the wall normal line load to the applied line load on the surface at

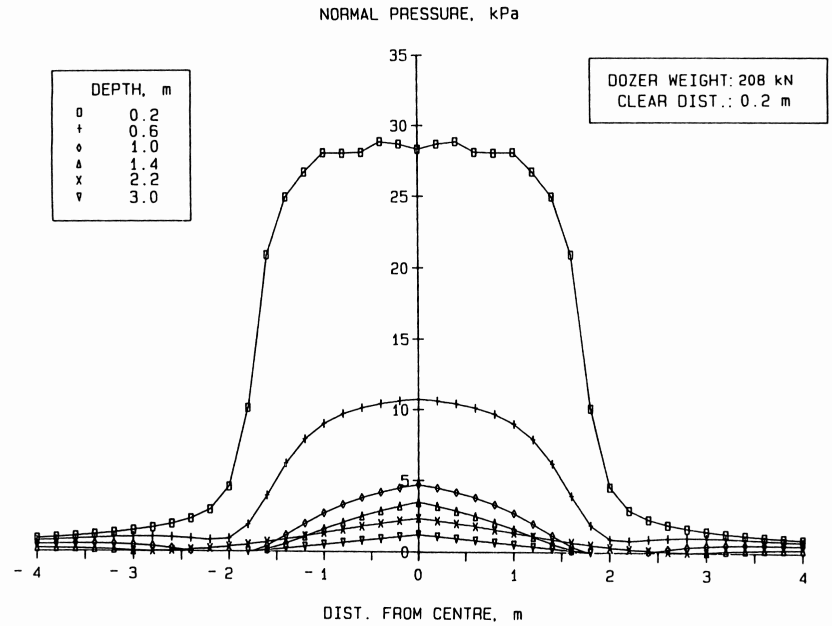



**Fig. 6. Normal wall pressures versus horizontal position due to a 21 tonne tracked vehicle positioned 0.2 m from the wall.**

the nearest distance from the wall is:

$K_f = L/L' = (15.1\ \text{kN/m})/(34.3\ \text{kN/m}) = 0.44$

Therefore, a design line load, $L$, acting at right angles to the wall can be estimated by:

$$L = K_f \cdot L' \tag{10}$$

where $K_f$ is a force ratio and $L'$ is the applied line load on the surface of silage. Equation 10 is recommended for estimating the wall normal line load due to compaction by a tracked vehicle. Further discussions on the force ratio will be given later.

### Load due to compaction by wheeled tractors

The variable pressure due to compaction by a 4.6 tonne wheeled tractor with the centre of a rear wheel (wheel load 16 kN) stationed 0.2 m away from the wall is shown versus depth in Fig. 7. The horizontal distribution of pressure is illustrated in Fig. 8. The pressures found by analysis were integrated to obtain a resultant force. For wheel loads of 16 kN, the resultant normal force on the wall is 7.8 kN. The ratio of the resultant to the applied wheel load is therefore:

$K_f = (7.8\ \text{kN})/(16\ \text{kN}) = 0.49$

Thus, a design load applied perpendicular to the wall can be estimated as:

$$P = K_f \times P' \tag{11}$$

where P is the concentrated design load perpendicular to the silo wall resulting from an applied wheel load of $P'$ acting on the surface of the silage, and where $K_f$ is a force ratio. It acts about 0.5 m from the silage surface. Appropriate design values for $K_f$ will be discussed next.

### Force ratio for compaction loading

Although the recommended design load from tracked compacting vehicle is a line load and that from wheeled

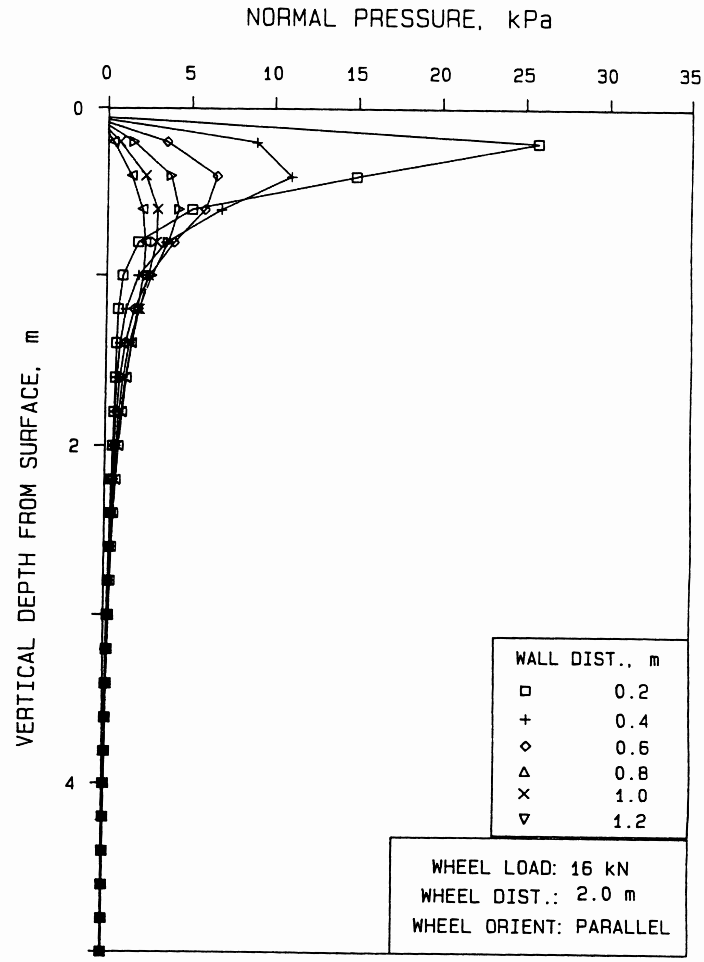



**Fig. 7. Normal pressures versus depth at the centre due to a wheeled vehicle with 32-kN axle load positioned 0.2, 0.4, 0.6, 0.8,1.0 and 1.2 m from the wall; axle perpendicular to wall.**

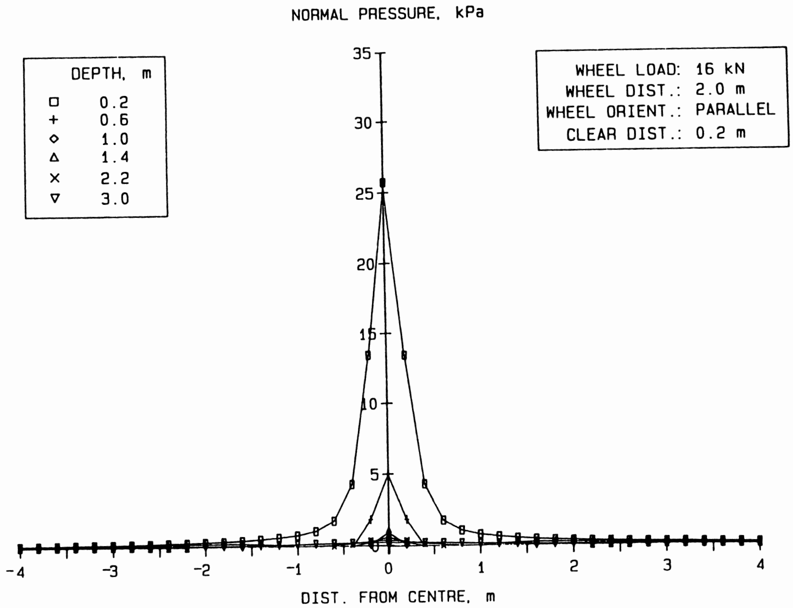



**Fig. 8. Normal wall pressures versus horizontal position due to a wheeled vehicle with 32-kN axle load positioned 0.2 m from the wall; axle perpendicular to wall.**

compacting vehicles a point load, both design load formulae take the same form (Eqs. 10 and 11). The values of the force ratios for the two cases computed in the previous section are very close; $K_f = 0.44$ for the tracked vehicle and 0.49 for the wheel tractor. These force ratios are also of the same order as those calculated with Eq. 9 for silage loads (Tables IV and V). The ratio for silage pressure on a silo wall with a slope of 10° and with flat silage surface is 0.642 if the wall-silage friction coefficient is 0.3. This ratio is greater than that for the tracked vehicle by a factor of 1.46 and that for a wheeled tractor by a factor of 1.31.

Analyses of wheel loads were also carried out for wall slopes of 0°, 5°, 10° and 15° following the same procedure. The resulting values for the force ratio in Eqs. 10 and 11 are provided in Table VI. As well, $K$ values determined from Eq. 9 are shown. They were calculated with the assumption that the silage surface was horizontal and that the friction coefficient between silage and wall was 0.4.

The pressure ratio computed with Eq. 9 is always greater than the force ratios obtained from Eqs. 10 and 11 by a factor ranging from 1.24 to 1.57. Considering that the calculated force ratios for tracked and wheeled vehicles do not include any allowance for an impact factor, it is considered appropriate that the force ratio, $K_f$, be taken equal to the pressure ratio $K$ calculated with Eq. 9. Equation 10 should be used for tracked vehicles and Eq. 11 for wheeled tractors. The line load (Eq. 10) or wheel load (Eq. 11) should be applied normal to the wall, 0.5 m below the silage surface, and in such locations as to cause the maximum effect. The line load should, of course, act parallel to the top of the silo wall.

**Table VI. Force ratios for vehicular loads, Eqs. 10 and 11**

| Wall slope | 0° | 5° | 10° | 15° |
|---|---|---|---|---|
| $K_f$ (Tracked vehicle) | 0.41 | 0.43 | 0.44 | 0.46 |
| $K_f$ (Wheeled tractor) | 0.41 | 0.45 | 0.49 | 0.53 |
| $K$ (Eq. 9) | 0.508 | 0.571 | 0.642 | 0.722 |

## SUMMARY

Based on a comprehensive study of pressures on horizontal silo walls from corn silage and compaction vehicles, simple formulae for determining design loads are presented. These formulae are sufficiently comprehensive to take into account the effects of wall slope, silage density and the manner in which silage is piled above the top of the wall. A summary of the design recommendations follow:

1. The normal wall load from corn silage can be estimated from Eq. 4, an expression commonly used for retaining wall design.
2. Silage bulk density can be estimated with Eq. 6.
3. The wall load due to compaction by tracked and wheeled vehicles can be approximated by Eqs. 10 and 11, respectively. The wall load from compaction is a live load and should be considered to act 0.5 m below the top of the wall, in the most unfavourable location. The line load is parallel to the top of the wall.
4. The pressure and force ratios in the above three formulae can be estimated as $1.65K_A$, where $K_A$ is the active pressure ratio computed with the Terzaghi's formula (Eq. 8) with an assumed internal angle of friction for corn silage of 29°.
5. Based on earlier work by Messer and Hawkins (1977a, 1977b, 1977c) it appears appropriate to use the design procedures in 1. to 4. above for all whole-plant materials.

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## NOTATION

- $g$ acceleration of gravity ($m/s^2$)
- $K$ pressure ratio
- $K_f$ force ratio
- $L$ design line load normal to silo wall (kN/m)
- $L'$ line load applied to silage surface (kN/m)
- $P$ design point load normal to silo wall (kN)
- $P'$ point load applied to silage surface (kN)
- $p$ normal wall pressure (kPa)
- $q$ vertical silage stress (kPa)
- $M$ gross mass of compaction vehicle (t)
- $z$ vertical depth below point at which silage surface intersects silo wall (m)
- $\alpha$ silage surcharge angle (degrees)
- $\beta$ wall slope with the vertical (degrees)
- $\delta$ wall slope with the horizontal (degrees)
- $\phi$ wall-silage friction angle (degrees)
- $\phi'$ internal angle of friction (degrees)
- $\rho$ silage density ($kg/m^3$)
- $\rho_d$ dry-matter density of silage ($kg/m^3$)

## REFERENCES


BSI. 1987. Code of Practice For Design of Buildings and Structure for Agriculture - BS 5502. British Standards Institution, London, UK.

CSA. 1988. Design of highway bridges. National Standard CAN/CSA-S6-88. Canadian Standards Association, Toronto, ON.

Darby, D.E. and J.C. Jofriet. 1991. Density of silage in horizontal farm silo. CSAE Paper No. 91-221. Saskatoon, SK: CSAE.

Esmay, M.L. and D.B. Brooker. 1955. Lateral pressures in horizontal silos. *Agricultural Engineering* 36(10):651-653.

Esmay, M.L., D.B. Brooker and J.S. McKibben. 1956. Design of above-ground horizontal silos. *Agricultural Engineering* 37(5): 325-327,333.

Hendrix, A.T. and J.R. McCalmont. 1958. Horizontal silos. ASAE Paper of the Georgia Section. St. Joseph, MI: ASAE.

Jaky, J. 1944. The coefficient of earth pressure at rest. *Journal of Society of Hungarian Architectural Engineers* 1944:355-358.

Jofriet, J.C., D.E. Darby and H. Bellman. 1988. Horizontal silo wall loads. CSAE Paper No. 88-118. Saskatoon, SK: CSAE.

Kangro, A. 1986. Load measurements in bunker silos for silage. Report 48. Division of Agricultural Building Technology, Swedish University of Agricultural Science, Lund, Sweden.

Le Lievre, B. and J.C. Jofriet. 1982. Determination of the mechanical properties of high moisture grain corn and haylage - phase II. Final Report submitted to Agriculture Canada, Engineering and Statistical Research Institute, Research Branch, Ottawa, ON.

Mayne, P.W. and F.H. Kulhawy. 1982. $K_o$-OCR relationships in soil. In *Proceedings of the Geotechnical Division, American Society of Civil Engineers* 108(GT6):851-871.

Messer, H.J.M. and J.C. Hawkins. 1977a. The loads exerted by grass silage on bunker silo walls. *Journal of Agricultural Enginering Research* 22:327-339.

Messer, H.J.M. and J.C. Hawkins. 1977b. The influence of the properties of grass silage on bulk density and horizontal pressure. *Journal of Agricultural Engineering Research* 22:55-64.

Messer, H.J.M. and J.C. Hawkins. 1977c. The influence of moisture content and chop length of forage maize on silage bulk density and the pressure on bunker silo walls. *Journal of Agricultural Engineering Research* 22:175-182.

NRC. 1983. Canadian Farm Building Code - NRCC No. 21312. National Research Council of Canada, Ottawa, ON.

NRC. 1990. Canadian Farm Building Code. National Research Council of Canada, Ottawa, ON.

Terzaghi, K. 1943. *Theoretical Soil Mechanics*. New York, NY: John Wiley and Sons.

Turnbull, J.E., D.I. Massé and W.S. Reid. 1987. Wall pressures for design of horizontal silos. Contribution No. C-00. Engineering and Statistical Research Centre, Agriculture Canada, Ottawa, ON.

Young, H. 1957. Pressure on walls in bunker silos. *South Dakota Farm Home Research* 8(4):16-18.

Zhao, Q. 1990. Bunker (horizontal) silo wall loads. Unpublished Ph.D. thesis, School of Engineering, University of Guelph, Guelph, ON.

Zoerb, G.C., H.G. Young, H.H. DeLong and D.L. Moe. 1959. Storage structures for grass silage. Bulletin No. 477. South Dakota Agricultural Experimental Station, Brookings, SD.