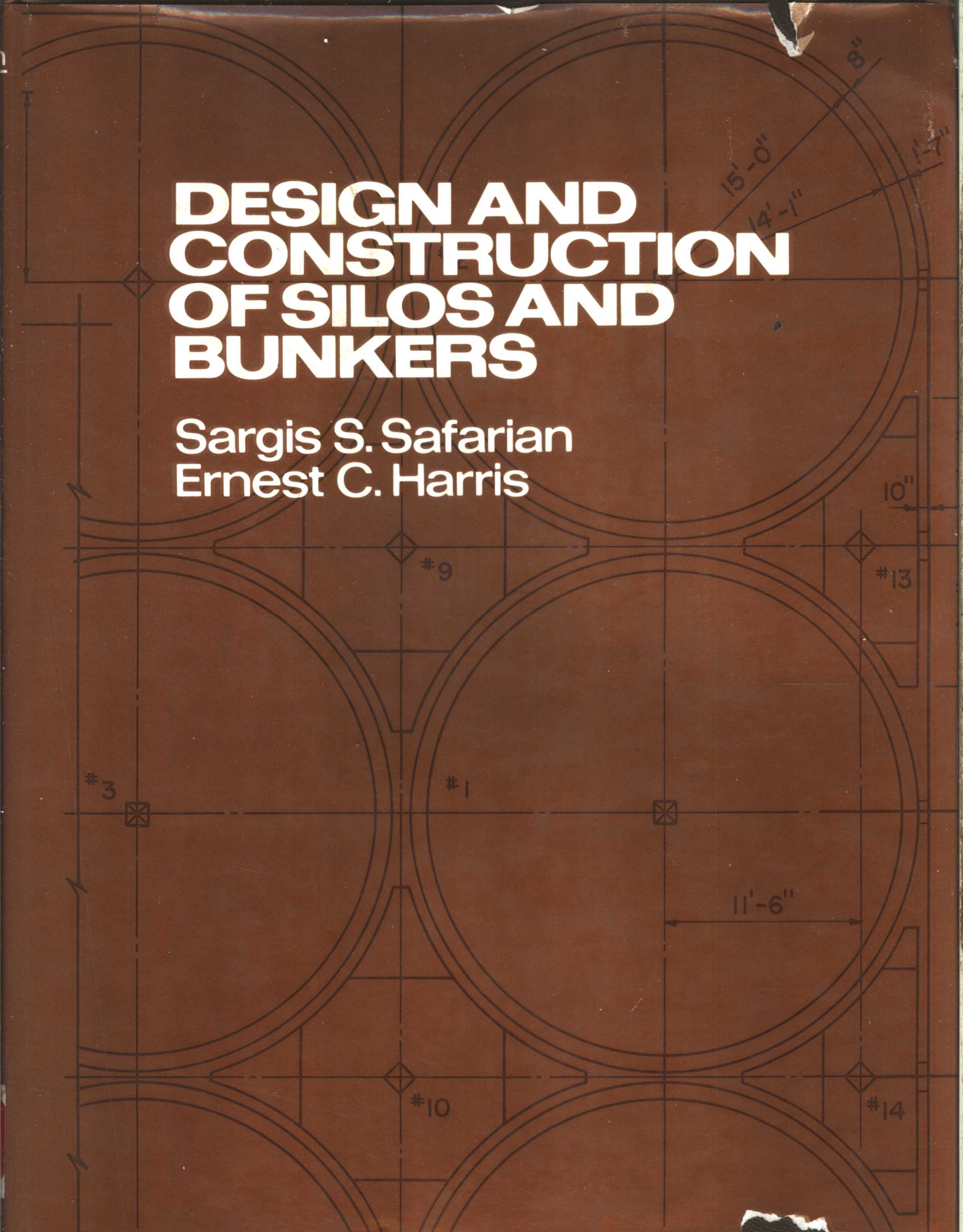

DESIGN AND CONSTRUCTION OF SILOS AND BUNKERS

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Preface

Storage silos and bunkers for bulk materials are in ever increasing demand, with the newer ones often surpassing any built previously in both capacity and complexity. Industry is also developing new uses for silos, beyond mere storage. These trends point to the need for an up-to-date, comprehensive presentation of structural analysis and design information to aid the designers, builders, and users of modern storage silos and bunkers for industry and agriculture. This book is written to meet that need.

The authors have drawn heavily on their own design and construction experience plus that of others in the United States and other countries. The book brings together technical information from many sources: technical papers, design standards, and design and construction codes.

In Chapter 2, "Stored Material Pressures," the classical methods for computing static pressures are presented first. Then a modern interpretation of material-flow characteristics is presented, followed by methods by Reimbert, Walker, Jenike, and others for computing total pressures, that is, static pressures plus overpressure. Requirements of various codes and standards are also discussed. Methods of including the pressure anomalies due to eccentric discharge are shown.

Following Chapter 3, "Silo and Bunker Loads," there are chapters devoted to the design of silos and bunkers of reinforced concrete, post-tensioned and precast concrete, steel, and less common materials such as wood and masonry. In most of these, design examples are presented to show methods that the authors have used successfully.

Silo failures have been quite common, and the engineer can learn much by studying them. The authors have been called to investigate many such cases. Chapter 10 describes failures and findings of various investigators and tells of the repair methods used. Since poor detail has been a frequent cause of distress, this chapter and the chapters on design give considerable attention to details.

It is our hope that this compilation of up-to-date design and construction information will help designers and builders of modern silos and bunkers to produce structures that are reliably safe, yet reasonably economical.

SARGIS S. SAFARIAN
ERNEST C. HARRIS

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Notations

A = area; interstice dimension (Fig. 4–19)
A_a, A_b = bottom areas tributary to walls a and b, respectively
A_g = total reinforcement area per unit width or per column
A_p = area of plate cross section
A_{ps} = area of prestressing steel per unit width
A_r = area of ring-beam cross section
A_s = area of stiffener, area of tensile reinforcement per unit width
A_s' = area of compression reinforcement per unit width
A_{sv} = area of reinforcement in vertical direction per unit width

B = hopper opening dimension; factor for Walker's method

C = Reimbert's characteristic abscissa; silo capacity; coefficient
C' = density coefficient for Platanov-Kovtun equations
C_b, C_e, C_g, C_N, C_r = overpressure coefficients (German Silo Code)
C_d = overpressure coefficient
C_i = impact factor
C_p = factor for seismic force computation
C_r = multiplying factor for raft foundation design
C_2, C_3 = factors for ring-beam analysis

D = diameter; dead load

E = modulus of elasticity; earthquake load
E' = welded joint efficiency factor
E_m = modulus of elasticity of stored material in compressed condition
E_1, E_2 = pressure increase factors for eccentric discharge (Theimer)

F = force; distribution factor for Walker's method
F_h = allowable horizontal inward force per unit length on ring-beam
F_m = meridional force per unit width
F_{ma}, F_{mb} = meridional force per unit width on walls a and b, respectively
F_t = allowable tensile stress; tangential force per unit width
$F_{t,a}$, $F_{t,b}$ = tangential force per unit width on sides a and b, respectively
F_{vu} = ultimate (factored) shear force per unit width

G = shear modulus of elasticity

H = horizontal force; height of storage zone

I = moment of inertia
I_s = moment of inertia of stiffener

K = torsion factor; factor for crack-width in walls with bending; coefficient for stave silo tests; prestress wobble coefficient
K_a, K_b, K_d = overpressure factors for Reimbert method for total pressures
K_L, K_g = load factors for dead and live load
K_t = coefficient for wall temperature gradient
K_2 = factor for ring-beam analysis
K, K_1, K_2 = constants for Ciesielski's method for nearly flat walls

L = length; live load; subscript meaning "live"
L_s = stiffener length

M = mass; moment; bending moment
M_p = 10 kN (ten kilo Newtons)
M' = moment applied to ring-beam by column
M_o = overturning moment
M_r = radial bending moment per unit width; horizontal loading moment in ring-beam
M_{sn} = service load bending moment for flexural crack-width computation
M_t = tangential (circumferential) bending moment per unit width; applied distributed torque
M_x, M_y = bending moment (per unit width) in x- or y-directions
M_{xtu} or M_{ytu} = ultimate bending moment in x- or y-direction due to temperature gradient

N = number (bolts, for example)

$P_{n,w}$ = nominal (theoretical) ultimate strength of wall per unit width
P_u = ultimate load

Q = force
Q_{cr} = approximate section modulus of cracked section
Q_{ep} = elastoplastic section modulus

R = hydraulic radius; temperature change ratio (for stave silos)
R_d = dome radius

S = section modulus; subcript for "secondary"

T = tensile force; temperature; period of vibration
T_b = anchor bolt tensile force

T_i = temperature of stored material
T_o = outside air temperature

U = cross-section perimeter

V = shear; seismic base shear; sum of vertical friction forces above point in question
V_c = nominal shear strength of concrete alone per unit width
V_w = total downward drag force

W = total weight of stored material; weight of designated structural element; distance between stiffeners

Y = depth of stored material above point in question

Z = earthquake zone factor

a = opening width; width of wall of rectangular or polygonal unit; coefficient for silage moisture
a' = fictitious length for side of rectangular silo

b = subscript meaning "bottom", wall width
b_{eff} = effective width

c = distance from neutral axis (or centroid) to extreme fiber; subscript meaning "column" or "concrete"; hopper dimension (Fig. 4–57)
c_a, c_b = coefficients for distributing bottom load to areas A_a and A_b
cr = subscript meaning "crack" or "critical"

d = effective depth of flexural section, from compression face of concrete to centroid of tensile reinforcing; subscript for "dead"; opening diameter
d' = distance from compression face of concrete to centroid of compression reinforcing bars
d'' = distance, extreme fiber on tension face of concrete to centroid of tensile reinforcing bars
daN = decaNewton (10 N)
des = subscript indicating "design" value

e = eccentricity; subscript meaning "emptying" or "earthquake"
e_1 = slenderness
ecc = subscript meaning "eccentric" or "eccentricity"
eff = subscript indicating "effective"
eq = subscript meaning "equivalent"

f = actual or computed stress; subscript meaning "filling" or "floor"
f_c = compressive stress; compressive stress in concrete
f'_c = unit compressive strength of concrete
f'_{ci} = unit compressive strength of concrete at time of wire wrapping
f_f = friction loss
f_{ps} = calculated stress in prestress steel at design load
f_{pu} = ultimate unit strength of prestressing steel
f_s = computed tensile stress in reinforcing steel
f'_s = computed compressive stress in reinforcing steel
f_{se} = effective stress in tendon steel (after losses)
f_{si} = average initial prestress in steel
f'_t = ultimate tensile strength of concrete
f_y = specified yield strength of steel

g = acceleration of gravity; subscript meaning "gravity"; factor for Ciesielski's method for nearly flat walls

h = wall thickness; overall depth of beam or slab; effective thickness of stave walls; subscript indicating "hopper"
h_c = effective head
h_o = height of wall opening

i = subscript meaning "imaginary"
i_ψ = factor for Caquot's equations

j = subscript meaning "juice"

k = ratio of horizontal to vertical pressure by stored material; stiffness
k_c = system stiffness

l = length; distance along a tendon; subscript meaning "live"
l_c = clear distance between supports

m = concrete shrinkage coefficient; subscript meaning "meridional" or "mean"; hopper shape factor; ratio of increase in k due to unit lateral pressure
max = maximum; subscript meaning "maximum"
med = subscript meaning "median"
min = subscript meaning "minimum"

n = number (columns or welds, for example); ratio of unit weight increase due to unit vertical pressure, modular ratio (E_s/E_c)
n_x, n_y = factors for triangular and trapezoidal plate analysis

o = subscript indicating "initial"

p = lateral pressure

q = vertical pressure by stored material

r = radius; subscript meaning "ring-beam"
r_b = bolt circle radius

s = subscript meaning "silage," "static," or "steel"
s_{cr} = crack spacing

t = subscript meaning "tangential," "total," "top," "thermal," "tensile," or "thickness" (see also h)

u = subscript indicating "ultimate" (i.e., factored)

v = subscript meaning "vertical" or "shear"
vert = subscript meaning "vertical"

w = weight per unit volume; radial displacement; load per unit area; fillet weld leg dimension; subscript meaning "wall"
w_{cr} = width of crack

w_1, w_2, w_3 = width of crack due to various loadings

x = subscript meaning "x-direction" or x-distance"
x, y, z = coefficients for curved interstice wall analysis (Timm and Windels)
$\bar{x}, \bar{y}$ = coordinates of centroid

y = subscript meaning "y-direction"
y_L = limiting depth of compression block

z = bracketed term on Janssen equation; abscissa for Reimbert's experimental curve

Δ = displacement (linear); deflection
ΔL = length of anchor set
ΔT = temperature difference, outside and inside wall faces

Σo = sum of reinforcing bar perimeters per unit width of wall

χ = factor for flexural crack-width computation
α = angle of hopper slope; factor for circular slab analysis; subscript for forces or pressures on sloping surface; angle change along tendon
α_t = linear coefficient of thermal expansion
β = factor for computing V and M due to tendon pressure; angle; factor for crack-width computation; factor for circular slab analysis

β_1 = ratio, depth of compression block to depth d

γ = weight per unit volume

δ = angle, used in curved-wall analysis; effective angle of friction (Jenike, Walker)

ζ = coefficient for Platanov-Kovtun equations; angle, for interstice curved wall analysis

η = angle between hopper plates; carrying capacity coefficient for grain arch (Platonov-Kovtun)

θ = angle of slope or rotation; angle around perimeter
θ_f = factor for computing shear due to tendon pressure

λ = factor for circular slab analysis or ring-beam analysis

μ = angle of friction (stored material against wall or hopper)
μ' = coefficient of friction ($\tan \mu$)
μ_t = curvature friction coefficient

ν = Poisson's ratio
ν_m = Poisson's ratio for compressed stored material

ρ = angle of internal friction for stored material, steel ratio
ρ_p = ratio of prestress steel area to gross concrete area

σ = stress

ϕ = strength-reduction factor

ψ = factor for computing vertical bending moment due to tendon pressure; factor for Caquot's equations
ψ_1, ψ_2, ψ_3 = factors for crack-width computation

ω = rotational frequency
ω_1 = angle, used in curved-wall analysis

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Chapter 1
INTRODUCTION

The custom of storing grain in upright containers is centuries old. Not until the mid 1800s, however, were relatively large storage containers built for commercial purposes. Since then, silos and bunkers have come into extensive use—not for storing grain alone, but for storing a wide variety of granular materials. In agriculture and industry alike, improved production methods and mechanization of handling have opened the way for large storage complexes, with sophisticated filling, unloading, and handling systems.

1-1. RECENT TRENDS

While earlier silos were only for more-or-less sedentary storage, the silo of today often plays an active role in the manufacturing and distribution process. Mixing, blending, proportioning—all are done using the silo as a vital part of the process system.

Recently, the desire to withdraw stored material faster has led to a demand for larger-capacity silos, having either greater height or greater diameter, or both. To be functional and economical, these larger-diameter silos generally have several discharge openings.

Each new trend brings new challenges to silo designers and builders. Frequently, meeting the challenge effectively has required research and experimentation. Although extensive research is done in Europe and Japan, the necessary research still lags behind the need, especially in the United States, where not much activity is reported in this field, except the work of Jenike[19–21] and Johanson.[96–101] Consequently, it is often the designer and builder who rise to meet the challenge using only

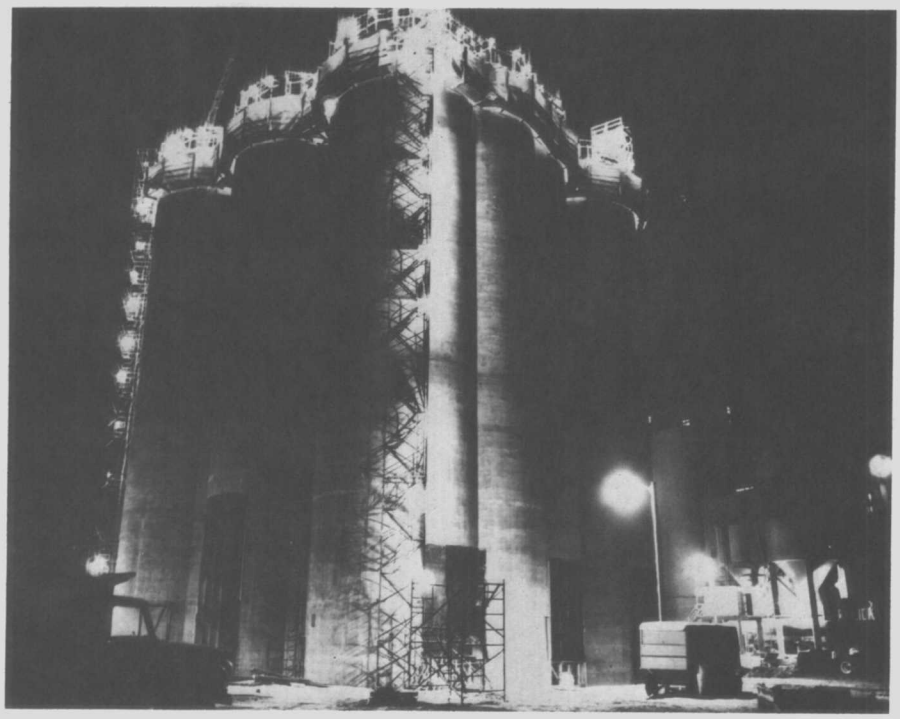

Plate 1-1. Around-the-clock slipforming of cement storage silos at Portland, Colorado. (*Courtesy of Ideal Cement Co.*)

Plate 1-2. Wood silo built in 1912 near Denver, Colorado.

Plate 1-3. Wood silo—corner detail.

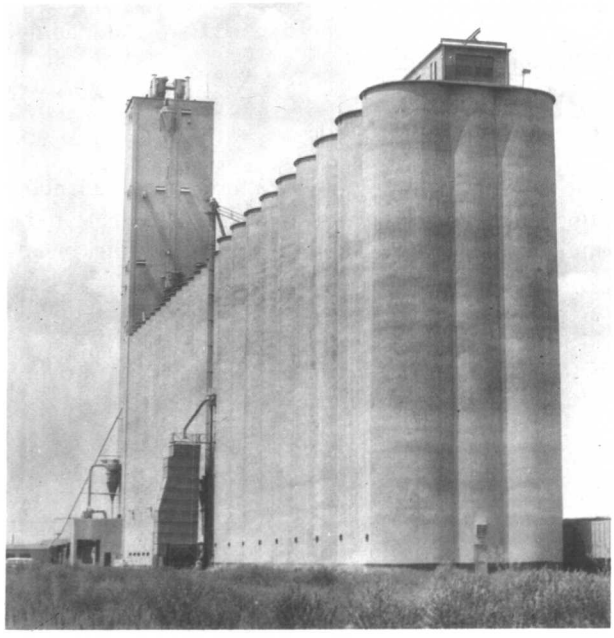

Plate 1-4. Grain elevator, a group of circular and horizontal silos, in Denver, Colarado. (*Courtesy of Cargill, Inc.*)

existing technology. An example is the application of post-tensioning to resist the large hoop tensile forces encountered in silos 70 ft or more in diameter. This use, while by no means a "cure all," did help to solve problems that would occur in large-diameter silos if conventional reinforcement had been the only alternative.

Much remains to be learned, yet remarkable progress has already been made in understanding the behavior of granular material in silos. This progress has resulted largely from years of experiments conducted in many parts of the world to study the pressures of stored granular materials against the walls and bottoms of silos.

Improved measuring techniques have been used with studies of material at rest and under various conditions of filling and emptying. These experiments reveal anomalies of pressure and pressure distribution that are important, yet not predictable by static-pressure computation methods.

As improved theoretical methods are developed to account for these anomalies, purely empirical methods can be abandoned. Then the realistic, practical, and safe design of silos and bunkers comes closer to reality. The list of contributors to this progress is impressive. It begins with Janssen[1] and Airy,[2] whose nineteenth century pioneering solutions as well as experimental work of Prante,[3] Jamieson,[4] Bovey,[5] Lufft,[6] and others (including his own), were presented by Ketchum.[7] In the beginning of the twentieth century such researchers as Tachtamishev,[8] Kim,[9] M. and A. Reimbert,[10] Platonov-Kovtun,[11] Caquot,[12] and others discovered shortcomings in the Janssen and Airy approaches. More recent studies by A. and M. Reimbert,[13] Pieper-Wenzel,[14] Pieper,[15] Theimer,[16,17] Nanninga,[18] Jenike,[19–21] Walker,[22] and many others[23–152] have further refined our understanding of stored-material behavior.

1-2. FAILURES

Despite such apparent progress in design and construction, silo and bunker failures still occur in all parts of the world, with large economic loss and frequent loss of lives.

Some of these failures are structural failures. Broadly, these may be categorized as due to: (1) design error; (2) construction error; and (3) user error. Design errors commonly involve inadequate pressures, buckling, improper details, or insufficient detail to guide the builder. Construction errors include mislocation, improper spacing, and omission of reinforcing, poor workmanship, and use of poor quality materials. User errors include storing materials other than those for which the structure was designed and modifying the system to change the manner or rate of discharge. Chapter 10 covers these problems and suggested repairs.

1-3. CODES AND STANDARDS

To help ensure safety and better-quality silo and bunker structures, several countries have already adopted codes and standards for silo and bunker design and construction. These include DIN 1055 Silo Code in Germany, CH 302 Silo Code in the Soviet Union, the French Silo Code, and the ACI 313 Standard Recommended Practice in the United States.

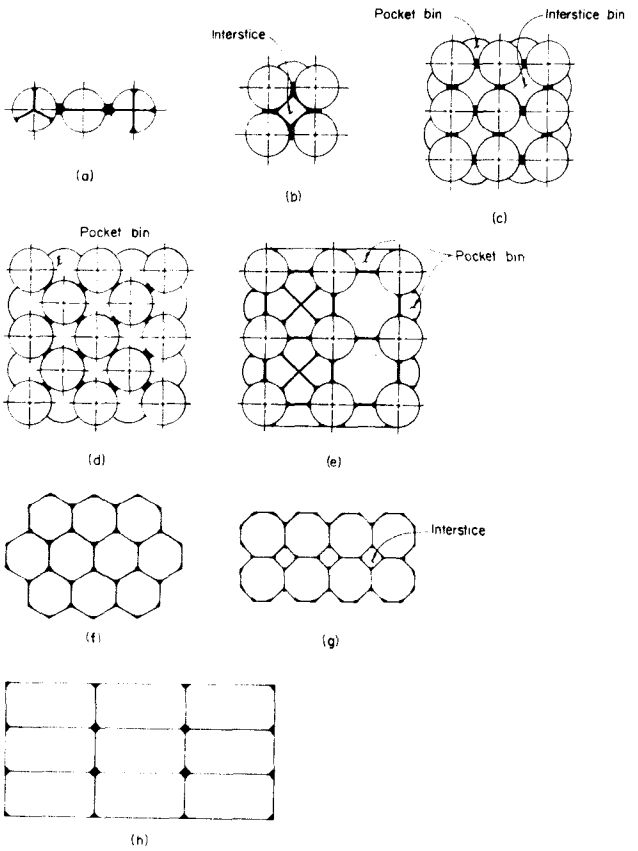

Fig. 1-1. Typical silo and bunker groups.

1-4. STORAGE FACILITIES

Storing of bulk materials in silos and bunkers is essential to agricultural, mining, mineral processing, chemical, shipping, and other industries. Silos and bunkers may serve for either long-term or short-term storage; commonly, though, silos serve as long-term storage facilities and bunkers as short-term. Both are used for storing finished materials as well as for intermediate storage of unfinished and raw products.

Silos or bunkers, either singly or in groups (Figs. 1-1 and 1-2), may serve as terminals for receiving and shipping. Such terminals usually involve multiple transportation modes; for example, material arriving by truck may be stored in the terminal temporarily and then discharged into train, barge, or ocean-going vessel for shipping elsewhere. Terminals usually have sophisticated systems for weighing materials being received and shipped.

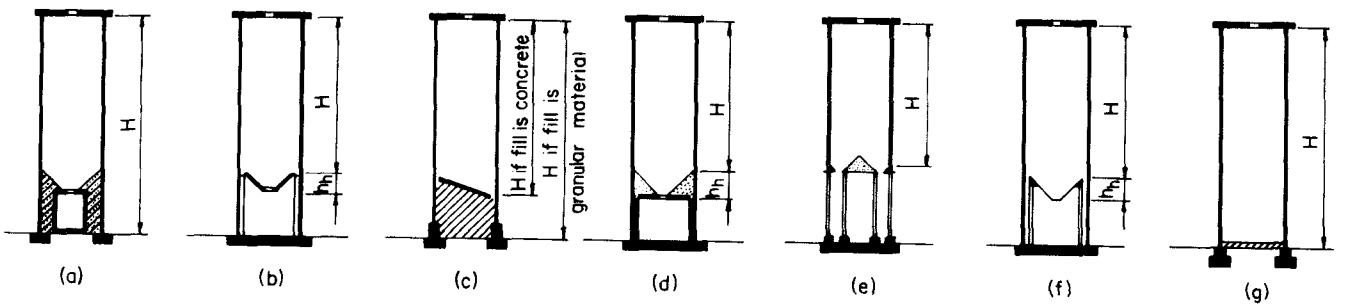

Fig. 1-2. Typical vertical cross sections of silos. (a) Silo walls on continuous footing, silo bottom consisting of tunnel and fill around and on top of tunnel. (b) Silo on raft foundation, independent hopper resting on pilasters attached to wall. (c) Silo with wall footing and independent bottom slab supported on fill. (d) Silo with hopper-forming fill and bottom slab supported on thickened lower walls. (e) Silo with multiple discharge openings and hopper-forming fill resting on bottom slab, all supported by columns; raft foundations has stiffening ribs on top surface. (f) Silo on raft foundation, with hopper independently supported by a ring-beam and column system. (g) Silo walls on continuous footing; bottom is a slab on grade.

Plate 1-5. Cement terminal at Wilmington, North Carolina. (*Courtesy of Ideal Cement Co.*)

Methods of loading and unloading silos and bunkers depend largely on the type of material to be handled and on economic and functional considerations. Loading is done: pneumatically (pumping, airslides, etc.); mechanically (conveyors, bucket elevators, etc.); and by gravity (dump cars, trucks, etc.). Emptying or discharging of stored material from the silo or bunker may be done: by gravity (direct, without help of any devices); mechanically (vibrating feeders, hoppers, vibrators, screw conveyors, etc.); and pneumatically (aeration, airslides, air jets, etc.).

1-5. CLASSIFICATIONS AND DEFINITIONS

The terms "bin," "silo," and "bunker" have different meanings in different parts of the world and may vary from author to author. In the United States the term "bin" generally includes both silos and bunkers, silos being deep bins and bunkers shallow bins.

The proportions of a bin—especially the ratio of material depth to least lateral dimension—affect the behavior of stored materials both at rest and during discharge. Assuming that bin geometry affects pressures, to select the proper basis for pressure computation the bin is classified either as a silo (deep bin) or a bunker (shallow bin). Accurate classification (which should also consider the flow condition) may soon be feasible, but presently the following methods are widely used in practice:

(a) *Empirical approximations*—preferred by many engineers. Two such approximations are:

1. By Dishinger[79]

$$H > 1.5A$$

2. By the Soviet Code[113]

$$H > 1.5D \text{ for circular silos}$$

$$H > 1.5a \text{ for rectangular silos}$$

If the storage structure in question satisfies *either* of the above, it is considered a silo. If it satisfies neither rule, it is considered to be a bunker.

(b) *An approximation based on the position of the plane of rupture*. Figure 1-3 shows bins of two different depths. The plane of rupture is determined by the Coulomb theory. Neglecting friction against the wall, for the case of a vertical wall and horizontal top surface, the Coulomb plane of rupture is midway between the angle of repose (ρ) and the vertical wall. (For other wall positions or surface slopes, the plane of rupture can be located analytically or graphically—by Culmann's method, for example.) [According to A. Reimbert,[13] the angle of rupture should be given by $(\pi/4 - \rho/3)$ rather than by the classic definition $(\pi/4 - \rho/2)$, both shown in Fig. 1-3.] If the rupture plane intersects the top surface of the stored material, the bin is a bunker (Fig. 1-3a), otherwise it is a silo (Fig. 1-3b).

However, engineers do not agree on the location of the plane of rupture. Some would start the plane at the bottom of the hopper, point C of Fig. 1-3b, while others would pass it through point D, at the bottom of the vertical wall. Thus, by one interpretation the bin would be a silo; by the other, a bunker.

Fortunately, for such borderline cases, exact classification is not critical. This is recognized by the ACI 313 Standard,[116] which, for simplicity and without significant error, allows all vertical containers, regardless of

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