An ACI Standard

Design Specification for Concrete Silos and Stacking Tubes for Storing Granular Materials (ACI 313-16) and Commentary

Reported by ACI Committee 313

ACI 313-16

American Concrete Institute
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First Printing
August 2016
ISBN: 978-1-945487-11-8

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This Design Specification provides material, design, and construction requirements for concrete silos, stave silos, and stacking tubes for storing granular materials, including design and construction requirements for cast-in-place or precast and conventionally reinforced or post-tensioned silos.

Silos and stacking tubes require design considerations not encountered in building structures. While this Design Specification refers to ACI 318 for several requirements, static and dynamic loading from funnel, mass, concentric, and asymmetric flow in silos; special loadings on stacking tubes; and seismic and hopper bottom design are also included.

Keywords: asymmetric flow; bins; funnel flow; granular materials; hoppers; mass flow; silos.

ACI 313-16 supersedes ACI 313-97, was adopted May 24, 2016, and was published August 2016.

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Introduction

This commentary presents considerations and assumptions in developing provisions of the Design Specification. Initial filling (static) pressures are exerted by the stored material at rest. Flow pressures differ from initial filling pressures, and are exerted by the stored material during flow.

Comments on specific provisions of the Design Specification are made using corresponding chapter and section numbers of the Design Specification. References cited in the commentary are listed in Chapter R10.

SPECIFICATION

CHAPTER 1—GENERAL

1.1—Scope

This Design Specification covers the design and construction of concrete silos, stave silos, and stacking tubes for storing granular materials.

For the design of these structures, initial filling and flow loading shall be considered. This Design Specification is supplemental to ACI 318-11 for design and ACI 301-10 for construction, where indicated.

1.1.1 *Specific inclusions*—Industrial stave silos for storage of granular materials are included in these specifications. The application to precast concrete is limited to industrial stave silos. Effect of hot stored material is included in this Design Specification.

1.1.2 *Specific exclusions*—Silos for storing silage are not included in this Design Specification. This Design Specification does not consider any chemical reaction between the silo reinforced concrete and the stored granular material. Three-dimensional dome structures are not included in this Design Specification.

1.1.3 *Hierarchy of standards*—Whenever the requirements of this Design Specification are more stringent than the requirements of ACI 318-11, the requirements of this Design Specification shall govern.

1.2—Documentation

1.2.1 Project drawings and specifications for silos shall be prepared under the direct supervision of and bear the seal of the licensed design professional.

1.2.2 Contract documents shall show all features of the work, naming the stored materials assumed in the design and stating their properties, including the size and position of all structural components, connections, and reinforcing steel; the specified concrete strength; and the specified strength or grade of reinforcement and structural steel.

COMMENTARY

CHAPTER R1—GENERAL

R1.1—Scope

Silo failures have alerted licensed design professionals to the inadequacy of designing silos for only static pressures due to stored material at rest. Those failures motivated researchers to study the variations of pressures and flow of materials. Research has established that pressures during withdrawal can be significantly higher (Turitzin 1963; Pieper and Wenzel 1964; Reimbert and Reimbert 1980, 1987) or significantly lower than those present when the material is at rest. The excess (above static pressure) is called overpressure, and the shortfall is called underpressure. One of the causes of overpressure is the switch from active to passive conditions that occurs during material withdrawal (Jenike et al. 1972). Underpressures can occur at a flow channel, and overpressures can occur away from the flow channel at the same level (Colijn and Peschl 1981; Homes 1972; Bernache 1968). Underpressures concurrent with overpressures cause circumferential bending in the silo wall. Impact during filling can cause the total pressure to exceed the static pressure. Whereas overpressures and underpressures are generally important in deeper silos, impact loading is usually significant for shallow bins (bunkers) in which large volumes of material are dumped suddenly. Some stored granular materials have sufficient cohesion and unconfined compressive strength to form large arches or cavities during discharge. The collapse of these arches and cavities can develop significant impact loads when the material above strikes the wall or floor. This document does not provide methods for calculation of such loads. The probability of forming arches and cavities can be reduced by using hopper and discharge equipment designs that reflect results from flowability testing of the stored material.

Overpressure, underpressure, or impact should be considered in the structural design of silos if present. Initial filling (static) pressures are exerted by the stored material at rest. Flow pressures differ from initial filling pressures, and are exerted by the stored material during flow.

R1.2—Documentation

Silos and stacking tubes are unusual structures. Many licensed design professionals are unfamiliar with computation of their design loads and with their design and detail requirements. Design computations and the preparation of project drawings and project specifications for silos, bunkers, and stacking tubes should be done under the supervision of a licensed design professional experienced in the design of such structures.

If possible, the properties of the stored materials to be used in the design should be obtained from tests of the actual materials to be stored or from records of tests of similar materials previously stored. Properties assumed in the design should be stated in the contract documents.

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1.3—Regulations/inspections

1.3.1 This Design Specification supplements legally adopted building codes in all matters pertaining to concrete silo and stacking tubes for storing granular materials.

1.3.2 Construction shall be inspected throughout the various work stages by or under the supervision of a licensed design professional or a qualified inspector.

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R1.3—Regulations/inspections

Investigations of silo damage and deterioration failures frequently reveal omitted or mislocated reinforcement, inadequate or misaligned reinforcement splices, and inadequate reinforcement cover.

The quality and performance of slipformed concrete silo structures depend on construction workmanship. The best materials and design will not be effective unless the construction is in accordance with project documents. For example, during slipform operations, the proper placement of reinforcement is a critical task. In addition, horizontal lifts, buckled jackrods, and concrete delaminations can occur if the concrete sets too rapidly, the slipform is improperly battered, or jackrods are overloaded. Similar considerations are associated with the quality and performance of jumpformed concrete silos.

Continuous field inspection of construction activity helps ensure conformance with the project requirements. The committee recommends that field inspection of construction activity be performed by or under the supervision of a licensed design professional. Field inspection of construction activity does not relieve the contractor of the responsibility to conform to project requirements.

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CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

The terms in this list are used in the Design Specification and as needed in the commentary.

A = effective tension area of concrete surrounding the tension reinforcement and having the same centroid as that reinforcement, divided by the number of bars; when the reinforcement consists of different bar sizes, the number of bars shall be calculated as the total area of reinforcement divided by the area of the largest bar used
$\bar{A}$ = critical ratio
A_f = area of flow channel, ft^2 (m^2)
A_s = area of hoop or tension reinforcement, in.^{2} (mm^2) per unit height
A_{silo} = cross-sectional area of silo, ft^2 (m^2)
A_w = effective cross-sectional area (horizontal projection) of an individual stave, in.^{2} (mm^2)
B = constant used to compute n
C_d = overpressure factor
D = silo inside diameter, ft (m)
D' = effective outlet diameter, ft (m)
d_c = distance from bar centerline towards surface, used to calculate design crack width, in
E = effects of earthquake or related internal moments and forces
E_c = modulus of elasticity for concrete, psi (MPa)
E_{cc} = distance from center of silo to center of outlet (eccentricity of outlet), ft (m)
E_p = modulus of elasticity of post-tensioning reinforcement, psi (MPa)
E_s = modulus of elasticity of reinforcement, psi (MPa)
e_o = distance from center of silo to apex of eccentric hopper, ft (m)
F_u = required hoop or horizontal tensile strength, lb (N), per unit height of wall
f_c' = specified compressive strength of concrete, psi (MPa)
f_{ci} = compressive strength of concrete at time of initial stressing, psi (MPa)
f_{pu} = specified tensile strength of prestressing steel, wires, or strands, psi (MPa)
f_{py} = specified yield strength of prestressing steel, wires, or strands, psi (MPa)
f_s = calculated stress in reinforcement at initial (filling) pressures, psi (MPa)
f_{se} = effective stress in post-tensioning reinforcement (after allowance for all losses), psi (MPa)
f_y = specified yield strength of nonprestressed reinforcement, psi (MPa)
H' = depth from the effective depth of the repose volume to the apex of the hopper, ft (m)
h = wall thickness, in. (mm)
h_b' = height from hopper apex to effective outlet of hopper, ft (m)

COMMENTARY

CHAPTER R2—NOTATION AND DEFINITIONS

R2.1—Commentary notation

The following additional terms are used in the Commentary, but are not used in the Design Specification.

A_s' = compression steel area, in.^{2} (mm^2)
d = effective depth of flexural member, in. (mm)
d', d'' = distances from face of wall to center of reinforcement nearest that face, in. (mm)
EI = flexural stiffness of wall, lb-in.^{2} (N-mm^2)
e, e', e'' = eccentricities, in. (mm)
F = radial force on the wall that results from the stressing (jacking) of the tendon, lb (N)
K_t = thermal resistance of wall, °F/in. (°C/mm)
M_{max} = maximum vertical bending moment per unit width of wall
M_u = required flexural strength per unit height of wall, ft-lb (m-N)
M_y = vertical bending moment per unit width caused by force F on the wall, ft-lb (m-N)
T_i = temperature inside mass of stored material, °F (°C)
T_o = exterior dry-bulb temperature, °F (°C)
V_{hy} = shear per unit width caused by a force F on the wall, lb (N)
V_{max} = maximum shear force per unit width of wall, lb (N)
$\underline{Y}_b$ = diameter of the flow channel at Level B, ft (m)
y = distance above and below tendon location, in. (mm)
β_p = factor relating to Poisson's ratio, silo diameter, and wall thickness
θ_c, θ_p = angle of conical or plane flow hopper with vertical, deg
θ_f = angle of flow channel with vertical, deg
θ_t = angle of flow channel axis with vertical, deg

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h_h = height of hopper from apex to top of hopper, ft (m)
h_s = height of sloping top surface (repose volume) of stored material, ft (m)
h_{st} = height of stave specimen for compression test, in. (mm)
h_y = depth below top of hopper to point in question, ft (m)
h_1 = core wall thickness, in. (mm).
k = ratio of p to q
L_w = length of design flow channel perimeter in contact with wall, ft (m)
l_{stg} = amount of vertical stagger between horizontal stave joints, ft (m)
M_{neg}= negative (tension outside face) circumferential bending moments caused by asymmetric filling or emptying under service load conditions, ft-lb (m-N) per unit height
M_{pos}= positive (tension inside face) circumferential bending moment caused by asymmetric filling or emptying under service load conditions, ft-lb (m-N) per unit height
M_t = thermal bending moment per unit width of height of wall (consistent units), ft-lb/ft (m-N/m)
M_θ = circumferential bending strength for an assembled circular group of silo staves, ft-lb (m-N) per unit height; the statical moment or sum of absolute values of $M_{\theta,pos}$ and $M_{\theta,neg}$
$M_{\theta,neg}$= calculated bending strength in the negative moment zone (tension on the outside face), ft-lb (m-N) per unit height
$M_{\theta,pos}$= calculated bending strength in the positive moment zone (tension on the inside face), ft-lb (m-N) per unit height
n = constant used to compute q_y
P_f = perimeter of flow channel, ft (m)
P_{nw} = nominal axial load strength of cast in place silo walls per unit area, psi (MPa), or hollow stave silo walls per unit perimeter, lb/ft (N/m)
$P_{nw,buckling}$ = nominal axial load strength of the stave wall per unit perimeter as limited by buckling, lb/ft (N/m)
$P_{nw,joint}$ = nominal axial load strength of the stave wall per unit perimeter as limited by the stave joint, lb/ft (N/m)
$P_{nw,stave}$ = nominal axial load strength of the stave wall per unit perimeter as limited by the shape of the stave, lb/ft (N/m)
p = initial (filling) horizontal pressure due to stored material, lb/ft^2 (N/m^2)
p_f = horizontal design pressure in a flow channel, lb/ft^2 (N/m^2)
p_n = pressure normal to hopper surface at a depth below top of hopper, lb/ft^2 (N/m^2)
p_s = horizontal pressure within static material around flow channel(s), lb/ft^2 (N/m^2)
q = initial (filling) vertical pressure due to stored material, lb/ft^2 (N/m^2)

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q_f = vertical design pressure in the nonconverging section of the flow channel, lb/ft^2 (N/m^2)
q_o = initial vertical pressure at top of hopper, lb/ft^2 (N/m^2)
q_s = vertical pressure within static material around flow channels(s), lb/ft^2 (N/m^2)
q_y = vertical pressure at a distance h_y below top of hopper, lb/ft^2 (N/m^2)
R_H = ratio of area to perimeter of horizontal cross section of storage space, ft (m)
R_f = ratio of area to perimeter for a flow channel, ft (m)
r = silo inside radius, ft (m)
s = bar spacing, in. (mm)
V = total vertical frictional force on a unit length of wall perimeter above the section in question, lb (N)
v_n = initial friction force per unit area between stored material and hopper surface, lb (N)
W = wind load, or related internal moments and forces, lb/ft^2 (N/m^2)
W_t = tension force per stave from wind overturning moment, lb (N)
w = design crack width, in. (mm)
w_s = width of stave specimen for compression test, in. (mm)
w_p = strength level wind pressure, lb/ft^2 (N/m^2)
Y = depth from the effective depth of the repose volume to point in question, ft (m)
$\bar{Y}$ = diameter of flow channel, ft (m)
Y_{EFF} = vertical distance from the top of the discharge opening to the effective depth of the repose volume, ft (m)
y = depth below top surface of a flow channel, ft (m)
α = angle of hopper from the horizontal
α_c = thermal coefficient of expansion of concrete, in./in. per °F (mm/mm per °C)
β = constant used to compute B
δ = effective angle of internal friction, deg
γ = weight per unit volume for stored material, lb/ft^3 (kg/m^3)
ϕ = strength reduction factor or angle of internal friction, deg
ϕ' = angle of friction between material and wall and hopper surface, deg
μ' = coefficient of friction between stored material and wall or hopper surface
μ_f' = coefficient of friction of flowing material
ν = Poisson's ratio for concrete, assumed to be 0.2
θ = angle of hopper from vertical, degrees
θ_f = angle of flow channel with vertical, deg
ρ = angle of repose, deg
ΔT = temperature difference between inside face and outside face of wall, °F (°C)

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2.2—Definitions

The following terms are defined for general use in this Design Specification. Specialized definitions appear in individual chapters.

aeration pressures—air pressures caused by injection of air for mixing or homogenizing, or for initiating flow near discharge openings.

asymmetric flow—flow pattern in which the flow channel is not centrally located.

concentric flow—flow pattern in which the flow channel has a vertical axis of symmetry coinciding with that of the silo and discharge outlet.

discharging—process of emptying the material by gravity from the silo.

effective angle of internal friction (δ)—a measure of combined friction and cohesion of material; approximately equal to the angle of internal friction for free-flowing or coarse materials, but significantly higher for cohesive materials.

expanded flow—flow pattern in which a mass flow hopper is used directly over the outlet to expand the flow channel diameter beyond the maximum stable rathole diameter.

expanded flow silo—silo equipped with a self-cleaning hopper section above a mass flow hopper section.

filling—the process of loading the material by gravity into the silo.

flow channel—channel of moving material that forms above a discharge opening.

flow pressures—stored material pressures during flow.

funnel flow—flow pattern in which the flow channel forms within the material; material surrounding the flow channel remains at rest during discharge.

hopper—converging portion at the bottom of a silo making the transition from a silo to one or more outlets.

initial filling pressure—pressures during filling and settling of material, but before discharge has started.

jackrod—vertical steel pipe or solid rod embedded in a silo wall, used in slipform silo construction; slipform lifting jacks are supported by and ride up the jackrods, advancing the wall forms vertically.

jumpformed silo—silo constructed typically using three segments of fixed forms; the bottom segment is moved to the top position after the concrete at bottom level gains adequate strength.

mass flow—flow pattern in which all material is in motion whenever any of it is withdrawn.

overpressure factor—multiplier applied to the initial filling pressure to provide for pressure increases that occur during discharge.

plane flow hopper—hopper with two flat sloping sides and two vertical ends.

pressure zone—that zone within the silo subjected either directly or indirectly to pressure from stored material.

pyramidal hopper—hopper with polygonal flat sloping sides.

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R2.2—Definitions

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rathole—flow channel configuration that, when formed in surrounding static material, remains stable after the contents of the flow channel have been discharged.

self-cleaning hopper—hopper that is sloped steeply enough to cause material, which has remained static during funnel flow, to slide off of it when the silo is completely discharged.

stable arch dimension—maximum dimension up to which a material arch can form and remain stable.

silo—any upright enclosed concrete structure with a bulk granular material stored against vertical walls.

slipformed silo—silo constructed using a continuously moving form.

stacking tube—relatively slender, free-standing tubular concrete structure used to lower material in a controlled fashion from a conveyor to a storage pile.

stave silo—silo assembled from small precast concrete units called staves, usually having tongue-and-groove joints, and held together by exterior adjustable steel hoops.

tilted hopper—hopper that has its axis tilted from the vertical.

transition hopper—hopper with flat and curved surfaces.

COMMENTARY

silo—the term “silo” includes both deep bins and shallow bins; the latter are sometimes called bunkers. Wherever the term “silo” is used in the Design Specification, it should be interpreted as meaning a silo, bin, or bunker of any proportion, shallow or deep.

stave silo—stave silos are used principally in agriculture for storing chopped silage, but are used for storing granular materials in other industries. The Design Specification covers industrial stave silos, but does not cover silos storing silage. The methods of computing pressures due to granular material are the same for industrial stave silos as for other silos. Design of stave silos, however, relies heavily on strength and stiffness tests; consequently, the Design Specification includes several design requirements that are peculiar to stave silos only.

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COMMENTARY

CHAPTER 3—REFERENCE STANDARDS

American Concrete Institute

ACI 117-10(15)—Specification for Tolerances for Concrete Construction and Materials and Commentary

ACI 301-10—Specifications for Structural Concrete

ACI 318-11—Building Code Requirements for Structural Concrete and Commentary

ACI 305.1-14—Guide to Hot Weather Concreting

ACI 306.1-90(02)—Guide to Cold Weather Concreting

ACI 308.1-11—Standard Specification for Curing Concrete

American Society of Civil Engineers

ASCE/SEI 7-10—Minimum Design Loads for Buildings and Other Structures

ASTM International

ASTM A47/A47M-99(2014)—Standard Specification for Ferritic Malleable Iron Castings

ASTM A123/A123M-15—Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products

ASTM A153/A153M-16—Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware

ASTM C55-14—Standard Specification for Concrete Building Brick

ASTM C309-11—Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete

ASTM C426-15—Standard Test Method for Linear Drying Shrinkage of Concrete Masonry Units

Post-Tensioning Institute

PTI M55.1-12—Specification for Grouting of Post-Tensioned Structures

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CHAPTER 4—MATERIALS

4.1—General

All materials and tests of materials shall conform to the ASTM standards specified in ACI 301. For materials that are not specifically provided for, the design strength and permissible stress shall be established by tests.

4.2—Cement and concrete

4.2.1 Cement shall conform to the requirements of ACI 301-10, 4.2.

4.2.2 The minimum specified concrete compressive strength shall be 4000 psi (28 MPa) at 28 days.

4.2.3 Concrete that will be exposed to cycles of freezing and thawing shall be air entrained. Air content shall not exceed that required by ACI 301-10, 4.2.2.4.

4.3—Aggregates

The nominal maximum dimension of aggregate for slipformed silo walls shall not exceed one-eighth of the narrowest dimension between sides of wall forms, or exceed three-fourths of the minimum clear distance between individual reinforcing bars or vertical bundles of bars.

4.4—Water

Water used in mixing concrete shall conform to the requirements of ACI 301-10, 4.2.1.3.

4.5—Admixtures

Admixtures used in concrete shall conform to the requirements of ACI 301-10, 4.2.2.5, and shall be subject to prior approval by the licensed design professional.

COMMENTARY

CHAPTER R4—MATERIALS

R4.2—Cement and concrete

R4.2.1 To minimize variations in concrete color, cement for exposed parts of silos or bunkers should be of one particular type and brand of cement.

In general, the types of cement permitted by ACI 318-11, 3.2, are permitted herein, except as noted. There is some variation in the physical properties of each type of cement. Type I cement that is very finely ground (a fineness modulus greater than 2000) can act in the same manner as Type III and cause placing difficulties by accelerating the initial set during a slipform operation.

Types IS and IP are not recommended for use in slipform or jumpform concrete because of long initial setting time and low strength at an early age.

R4.2.2 Performance and design requirements for concrete mixtures should meet the requirements of ACI 301-10. Concrete mixtures should be proportioned to produce a required average compressive strength determined in accordance with ACI 301-10.

Historically, concrete mixtures with a slump of 4 in. (100 mm) have been used successfully for construction of slipformed silo walls under a variety of field conditions. High-range water-reducing admixtures have been successfully used to increase slump without adversely affecting the water-cement ratio (*w*/*c*) or strength.

R4.2.3 Concrete is considered exposed to freezing and thawing when, in a cold climate, the concrete is in almost continuous contact with moisture before freezing. Entrained air in concrete will provide some protection against damage from freezing.

R4.5—Admixtures

The use of admixtures in concrete silo walls is a common method of controlling the initial set of concrete and, therefore, the rate at which slipforms or jumpforms may be raised.