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Design Considerations for the Construction and Operation of Grain Elevator Facilities. Part I: Planning, Structural, and Life Safety Considerations

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Abstract. *Grain elevators represent a major link our food production system. To date, information about the unique design requirements of these facilities has been limited. In an effort to summarize state of the art design procedures for grain elevator facilities constructed in North America, an overview of accepted standards and procedures has been assembled. With this paper engineers should become more familiar with specific design considerations for grain handling facilities and develop appropriate references to expand their knowledge base. Educators may find this paper useful too.*

Keywords. Agri-Industry, Concrete, Foundations, Grain Elevators, Life-Safety, OSHA, Planning, Steel, Structural Design.

Introduction

The commercial grain elevator system represents one of the first steps from the farm to the table in the North American food and fiber production system. Grain elevators play a major role in the distribution and sale of agricultural commodities. According to the Census Bureau Report, there are 6,514 businesses that operate grain elevator establishments in the United States (US Census Bureau, 2004). Although a number of contractors and engineers service this industry, the operation and design grain handling facilities have unique requirements that have not been thoroughly documented to date. Additionally, the number of engineers and contractors servicing this market segment is diminishing, thus, the purpose of this article is to summarize state of the art standards and procedures for the design and construction of grain handling facilities and improve the knowledge base of the industry.

Overview of a Grain Handling Facility

Grain elevators store and handle a variety of agricultural commodities, including corn, soybeans, wheat, barley, rice, canola, flax, etc. Some facilities handle a variety of commodities; others will strictly handle only one type of commodity. There are two major types of grain handling and storage facilities: country and terminal elevators. Country elevators are the smaller local grain elevator facilities that are serviced by trucks, wagons, and limited rail access. They tend to serve a smaller geographical area, often a rural community. The terminal elevator is a gathering point for the commodities collected from the country elevators. Terminal elevators can be further classified as inland and port elevators. They are structured to receive grain from truck, rail, or ship, and usually ship outbound grain via ship or rail. Terminal elevators are distribution points for export or wholesale to food process or feed companies.

There are two major types of facility layout for grain elevator facilities: traditional or modern. Traditional layout and design of grain elevators incorporates the equipment into an enclosure on top of the silos, which is known as a head house. The grain in this type of facility arrangement is conveyed to the individual silos by a large gallery type conveyor. In the more modern type of grain elevator design, major equipment such as the distribution and/or conveying system is external to the grain elevator. Typically the modern design is mainly driven by the need to eliminate dust explosions.

Storage types for grain elevators include: (1) flat storage, (2) smooth wall steel bins, (3) corrugated steel bins, and (4) concrete bins. Flat storage consists of a pre-manufactured metal building or grain piles on the ground covered by a tarp. Smooth wall steel bins are typically used when smaller quantities of grain are stored. Corrugated steel bins offer economical storage in large quantities and are represented by a large number of commercial manufactures in the United States. Concrete silos are an initially a more expensive option, but generally are least subject to wear, thus lasting longer. Recently, they have become even more economical with the higher prices of structural steel. Generally, silos are round as this is the most efficient and economical design, but six or eight sided bins have been built from both steel and concrete in North America and Europe.

Features of a typical grain handling facility include (1) receiving, (2) load out, (3) reclaim, (4) storage, (5) drying, and (6) cleaning. Country elevators will have the ability to receive from trucks or farm equipment, and the load out area will typically be to rail and semi truck. Most country elevators will use lighter storage including corrugated bins. A portion of the country and terminal elevators will have drying and/or cleaning areas. The terminal elevators will likely have receiving and load out for rail and truck. All terminal elevators adjacent to water will have

receiving and shipping via waterborne vessels. These elevators are more likely to have storage constructed of concrete, due to high throughputs.

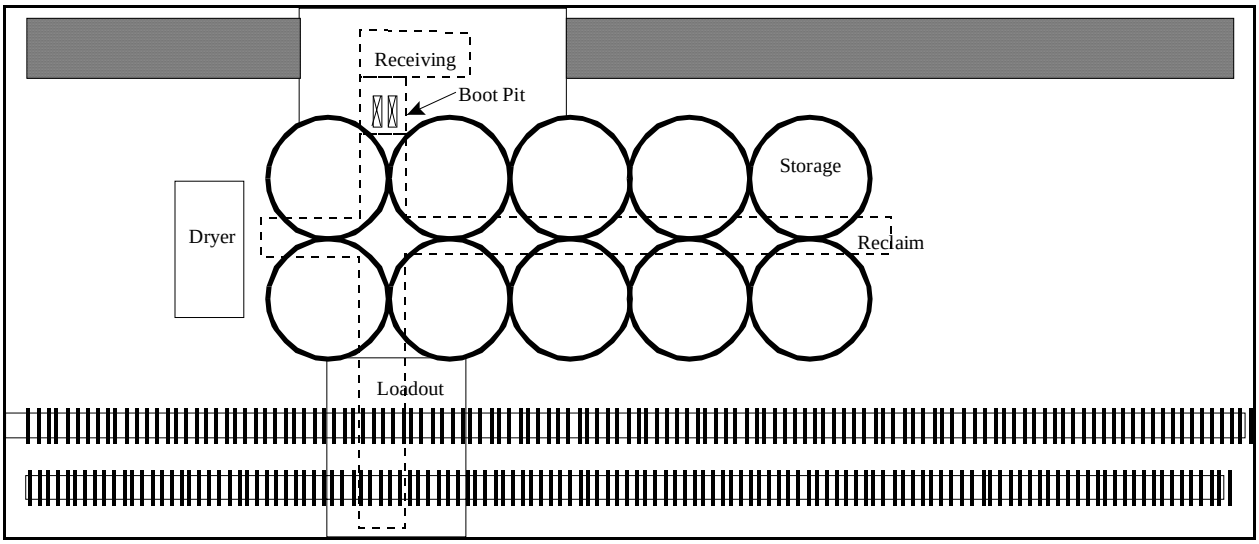

Figure 1. Schematic showing a typical terminal grain handling facility and its components.

Facility Planning Considerations

Proper planning is an important aspect of long-term profitability for a grain handling facility. It is important for engineers of these facilities to minimize these costs to increase value for owners and shareholders. A major part of effective planning is considering items such as (1) long range planning, (2) economic factors, (3) regulatory issues, (4) location/site, and (5) facility expansion versus new construction. Optimal planning should lead to lower life cycle costs. These are detailed as follows:

- Long range or strategic planning is a function of the strategic vision and objectives of an organization. It generally reflects the mission of the company and how it will proceed toward achieving its business objectives. For optimization of long-range profitability, capital spending on new facilities needs to reflect the strategic planning objectives of the organization.
- Economic considerations for the operation of a facility can have a major impact on its profitability. Local issues such as grain types and volumes produced in a particular geographic location, the availability of transportation, and the number of existing facilities in a particular geographic area will directly affect the economic success of a grain handling facility. Global economic issues such as long-term increases in population, which in turn can increase demand, can also be a consideration. Additionally, the eating habits of the demographic population or the processing capabilities of regional industries may have an influence on production demand. Finally, Return On Investment, or ROI, should be a major consideration in the decision to operate a new facility.
- Governmental and political issues can have a significant effect on the need for a grain elevator facility in a particular region. Global issues such as GMP and identity preservation can have a major effect on international demand for product. Inside the United States, there are a number of regulations from both the EPA and USDA that can influence the design and operation of a grain handling facility.

- Selection of an appropriate site is an important consideration for the profitability of a grain handling facility. Locations close to applicable transportation and infrastructure are essential for grain elevator operation. Existing port operations may also be helpful. Dock or river operations are desirable for inland terminal operations. Functional rail facilities are essential for most grain handling operations. Appropriately rated roads and highways are also essential for all gain elevator operations. The availability of existing storage or conveying systems may be beneficial for an owner if they are in good condition.
- Once a decision has to be made to build a facility in a specific geographic region, the owner and engineer must examine if a currently existing facility in the area can be expanded or upgraded first. If the discounted cash flow of the cost of the upgrades is greater than new construction then consideration should be given construction of a new facility.
- Facility layout and design is a key consideration in the operation of a functional facility. The relative location between physical locations of the receiving and load out, or possibility for double duty, can play a role in the operational costs of running the facility. The type of construction and the amount of available land can have major role in the physical layout of the facility. For example, a loop track for a 110-car rail shuttle loading system can require a vast amount of land. Issues such as explosion or fire safety can influence the physical layout of a facility. Finally, the budget that the facility owner has available can dictate the types and sizes of construction that can be pursued.

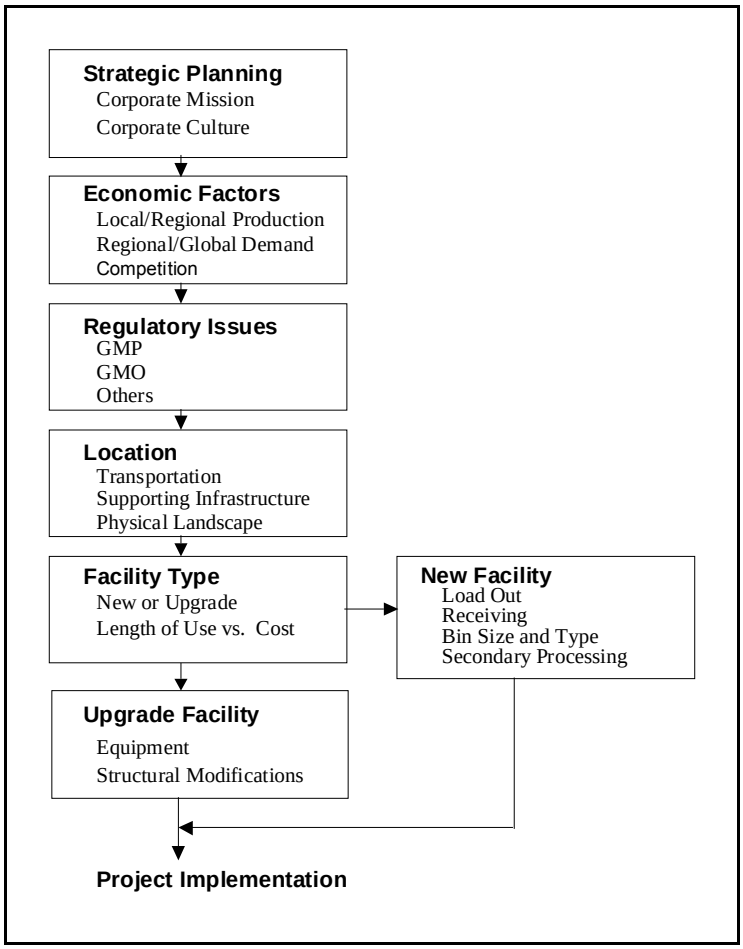

Figure 2. Flow chart of feasibility planning.

Life Safety Design Considerations

Once the decision to build has been made by the owner and engineer, the life safety and structural planning can begin. Life safety codes are administered at state, local, and federal levels. Federal regulations, such as Occupational Safety and Health Administration standards from Title 29 of the Federal Code of Regulations (NARA, 2004), and state-adopted model codes such as the International Building Code (ICC, 2000) dictate how facilities are planned and constructed. Highlights of these codes, as they relate to grain handling facilities, are discussed in the following sections. Figure 3, at the end of the section provides a flow chart showing the interrelationship of the life safety concepts. Table 1 summarizes the major sections of the life safety codes

Model Building Codes

The main building code in the United States is the International Building Code (IBC), which is the model code for forty-eight of the fifty states (ICC, 2000). The IBC defines a number of life safety related issues including occupancy types, construction types, height and floor area, egress, stairs, access, and a number of other major life safety issues. Some of the major items of consideration in the IBC are summarized in table 1 and detailed in the following subsections.

Use and Occupancy Requirements

Chapter 3 of the International Building Code specifies ten different Use and Occupancy types for facilities. For specifics, the reader is referred to the IBC, but these categories range from residential to hazardous industrial. Occupancy loads are defined in table 1003.2.2.2 of the IBC. Common Use and Occupancy Types typical for grain facilities include:

- Group B - Business - The business or laboratory sections of a grain handling facility may fall under this occupancy.
- Group H-2 - Hazardous – Grain elevators that store agricultural commodities that shed substantial levels of fine dust fall under this category. Under the appropriate conditions, this dust can be highly explosive. Further processing areas such as grinding systems would fall under this category too.
- Group F - Factory and Industrial – Non-hazardous building processing operations would fall under this category. Examples include further processing that does not produce explosive dust such as packaging or cooking operations that exist in many agri-industrial facilities.
- Group S – Storage. Generally this classification is used for the noncombustible storage of goods. If the dust produced by the stored commodity in a grain elevator were non-explosive, it would be category S.

Construction Type

Construction type influences the height and area of the buildings in a grain elevator facility. There are four major construction types defined in the IBC (ICC, 2000). They vary from a highly protected Type I construction to the least protected Type IV construction. They are further divided into subcategories of A and B, which define additional levels of added fire protection. Generally, construction Types II and I consist of masonry, steel, and concrete structures. Type III construction has noncombustible exterior walls and interior materials of any material. Type IV construction, heavy timber, is not commonly used in agri-industry. Type V construction is

construction where any combustible or non-combustible material is used for construction and is applied to construction types that do not qualify for Types I to IV construction.

Height and Floor Area

Allowable height and floor area are a function occupancy type and construction type. Most grain elevators fall under classification of H-2, and under the exception in 415.7.1, are allowed to be unlimited in height when they are Type I or II construction (i.e. concrete or steel). Rarely are grain handling facilities of another material type (e.g. timber), so almost all grain elevators can be unlimited in height. Table 503 in the IBC defines allowable heights and areas. According to table 503, type I or II construction allows floor areas to vary from 7,000 to 21,000 square feet per level. Other maximum areas for business and administrative areas are also found in table 503.

Location on Site

As outlined under the special requirements section, grain elevators cannot be closer to the edge of a property line or adjacent structures than 30 ft except in cases where the railroad right of way can run adjacent to the structure. The engineer should be aware of the required rail clearances and work closely with the railroad to define these necessary clearances. Site location for other secondary structures on a grain handling facility is shown in Table 602 of the IBC (ICC, 2000) and is dependent on the fire ratings of the exterior walls of the building under consideration.

Special Requirements in the IBC

Once the occupancy and type of construction are established, then the engineer will need to determine specific special occupancy requirements that relate to the special features of the facility. Chapter 4 of the International building code outlines a number of building code requirements relating to grain elevator design and construction. These special requirements are outlined below:

- IBC 415.7.1.5 - States that grain elevators must be located at least 30 ft from a lot line, or adjacent structures, except at the railroad right of way. This requirement allows grain elevators to be adjacent to rail lines, which is a major mode of commodity transportation, but keeps the facility away from adjacent structures where the hazards of a dust explosion could cause an injury.
- IBC 415.7.1 - States that Type I and II construction for grain elevators is unlimited. For other construction types the engineer should follow use table 503. Type I and II construction includes all metal and concrete grain elevators, thus effectively including the all constructed grain elevators. Since the early 1960's very few grain elevators have been constructed using wood.
- IBC 415.7.1.2 - Requires that grinding rooms 3,000 square feet or less requires a 2 hour fire rating. A 4 hour fire rating is required if the grinding room is 3,000 square feet or more. Grinding rooms, which are common in grain and feed facilities, must be isolated from other areas of the facility. Often times it is necessary to have explosion panels on the exterior of the walls of this portion of the facility. Specific requirements are detailed in NFPA 68.
- IBC 415.7.1.4 - Requires dust tight spouting and conveyor covers. This requirement reflects the inherent explosion hazard in grain handling and storage facilities.

- IBC 415.1.7. - States that grain elevator design must follow NFPA 61, 65, 85, 120, 651, 655, and 664, where applicable. The major standard fundamentally related to grain handling facilities is NFPA 61, which addresses the dust handling hazards in agricultural and food process facilities.

Guard Rails

Guard rails are an important feature for roofs, elevated platforms, and mezzanines. Section 1003.2.12 of the IBC states that guards are required for open sided walking surfaces such as platforms, mezzanines, and equipment access platforms. In most industrial situations, the guards must be arranged such that a 21-inch diameter sphere cannot pass through the rails. This usually requires the use of a mid rail. The requirements for guards and stair handrails are different and should be noted by the engineer before proceeding with the project.

Stairs

According to IBC section 1003.3.3, a 44-inch wide stairway is required. If the occupant load is less than 50 people, then a 36-inch wide stairway is required. Stair slopes in the IBC are more restrictive than older building codes, or OSHA, with a typical 7-inch rise as the maximum rise and an 11-inch run. For steeper stair slopes, such as an 8-inch rise with a 9-inch run, a variance must be obtained. The engineer should coordinate with the local building code officials as early as possible during the project planning phase, to help with this important issue. Additionally, the engineer should be aware that stair landings will be required every 12 feet. This has a substantial impact on the resulting height of a structure, due to the size of the stairwell. Finally, section 1003.3.11 of the IBC gives the handrail requirements for stairs. These requirements vary significantly from guardrails.

Exiting and Egress

Exiting and egress is covered in section 1005 in the International Building Code. Generally speaking, for occupancy type H-2, with an occupancy load of three or more people (Table 1004.2.1); there must be two independent exits from each floor or area. Exit discharge is described in section 1006 and occupant loads is defined in table 1003.2.2.2. Two areas of concern for facility engineers and operators are the egress from the roof of the structure and from tunnels. Usually in a grain elevator the man lift and either an exterior ladder system or an internal stair system provide the two methods of egress from specific floor levels. Egress ceiling heights should not be less than 7 feet.

Mezzanines

Section 505.1 of the IBC discusses mezzanine design and construction. In general, it states that a mezzanine should not be counted as part of the floor below and shall not cover more than 1/3 of the floor area of the room it occupies for purposes of building classification, but, similar to other areas of the building, is required to have two independent means of egress.

Equipment Access Platforms

Equipment access platforms are a special form of a mezzanine and are discussed in section 505.5 of the IBC. In general, the total of all equipment platforms should occupy less than two-thirds of the building area, and for purposes of occupancy classification shall not add to the floor area of the building. Access equipment that is attached to the platform such as stairs, ladders, walkways, and similar access shall not serve as part of the egress system for that building level.

Building Envelope

Grain elevators are unheated and do not need to meet any special energy requirements with respect to the energy portions of the building code. The engineer should be aware that the temperature may affect the quality of the contents, however.

Fire Protection

There are no explicit fire protection requirements for grain elevators other than those given in the referenced NFPA documents and the given construction types for grain elevators.

OSHA

OSHA standards are set out in Title 29 of the Federal Code of Regulations (NARA, 2004). These standards set workplace safety, and are considered a minimum that must be met for non-public operational areas of facilities. They cover a number of construction related issues such as access, exits, fixed ladder construction, stairs, ships ladders, guardrails, equipment access, and tunnel construction. Most items relating to constructed facilities are in section 1910 of Title 29. OSHA standards are also of significant importance to facility operators as they influence a number of operational items relating to worker safety. OSHA standards are only enforced if more stringent than the controlling building code. These items are outlined in Table 1.

House Keeping

Good housekeeping and dust accumulation prevention will limit the potential hazard of dust explosions. Key to this issue is adding dust sheds to roof beams, receiving pit beams, and other areas where significant amounts of dust will accumulate. Dust control also involves the addition of baffles in the receiving areas. The engineer plays a major role in assisting the owner with good housekeeping techniques during design and construction.

Supplemental Codes and Standards

The International Building Code specifies that specialty facilities must incorporate a number of special design provisions. Chief among these is the Nation Fire Protection Association (NFPA) documents outlined below.

- NFPA 68 – Guide for venting of deflagrations (NFPA, 1998a) - This standard covers the design and installation of devices and systems to relieve pressures and gasses that result from explosions. It also includes information on the calculation of explosion pressures. This standard is commonly used in the grain industry to determine bucket elevator venting and venting for silos that contain powder-like agricultural substances, such as flour.
- NFPA 69 – Standard on explosion prevention systems. (NFPA, 1998b) This standard covers the design, construction, operation, maintenance, and testing of systems for the prevention of explosions. This document covers the prevention of explosions by the following methods (1) control of oxidant concentration, (2) control of combustible concentration (3) explosion suppression (4) deflagration pressure containment, (5) spark extinguishing systems. This standard is not usually applied to grain elevators, except in rare instances.
- NFPA 61 – Standard for the prevention of fires and dust explosions in Agricultural and Food Products facilities. (NFPA, 1999) As the name implies, NFPA 61 is a standard that relates to dust explosion safety in Agri-industrial process facilities that handle bulk materials. This document covers construction requirements such as egress, interior wall construction, building fire protection, and equipment including: dryers, venting, heat transfer operations, dust control, pneumatic conveying, and building fire protection.

Table 1. Design matrix for grain elevator life safety considerations.

Code Item	Description of Application	Code Section/Requirements
IBC		
Occupancy	Determined based on the use of the structure. E.g. hazardous, manufacturing, business office. Methods of calculation for mixed occupancy	Chapter 3 outlines occupancy types. Grain elevators are typically Group H-2. Further processing may be Group F. Business office may be group B. Group S occupancy if dust is non explosive
Detailed Requirements Based on Use and Occupancy	Special requirements for the construction of hazardous facilities such as grain elevators or feed mills	Chapter 4 section 415.7
Types of Construction	Based on the materials used and the fire resistance of the components. Most grain elevators are Type I and II construction	Chapter 6.
Location on Property	Location of the structure on the site. Influences the fire rating. Special lot line distances are defined in Section 415.7.1.5	Chapter 6 section 602
Floor Area	Maximum floor area is a function of construction type and occupancy	Chapter 5, table 503
Height and Number of Stories	Influenced by floor area, construction type and fire protection. See Section 415.7.1 for height requirements	Chapter 5, table 503
Fire-Resistance-Rated Construction.	Code prescribed requirements for materials and assemblies used to separate adjacent areas and prevent the spread of fire and smoke	Chapter 7
Stairs	Design of stair stringers, rise and run, and stair construction details	Chapter 10, section 1003.3.3
Guard Rails	Design of guard rails, construction requirements for walkways, stairs, and openings	Chapter 10, section 1003.2.12
Mezzanines	Special construction applications	Chapter 5 section 505.1 and 505.5

Table 1 cont. Design matrix for grain elevator life safety considerations.

Code Item	Description of Application	Code Section/Requirements
Egress	Egress fire ratings, size, occupant loads, arrangement	Chapter 10
OSHA		
Egress	Egress fire ratings, size, occupant loads, arrangement	Section1910.37
Tunnels	Noted in the egress section. Two methods of exit required.	Section 1910.37
Guard rails	Structural design of guard rails, construction requirements for walkways, stairs, and openings	Section 1910.23
Man lifts and Powered Platforms		Section 1910.66
Fixed Industrial Stairs	Structural design of stair stringers, rise and run, and stair construction details	Section 1910.24
Fixed Ladders	Features, clearance, hatches, cages, offsets, and landings	Section 1910.27
NFPA		
61 – Dust and Fire Control in Agricultural Facilities	A major design requirement for equipment such as bucket elevators, conveyors and the like.	NA
68 – Guide for venting of Deflagrations	A guide for the design and construction on explosion forces and explosion panels	NA
69 - Standard on explosion prevention systems	A guide for the design of explosion prevention systems	NA

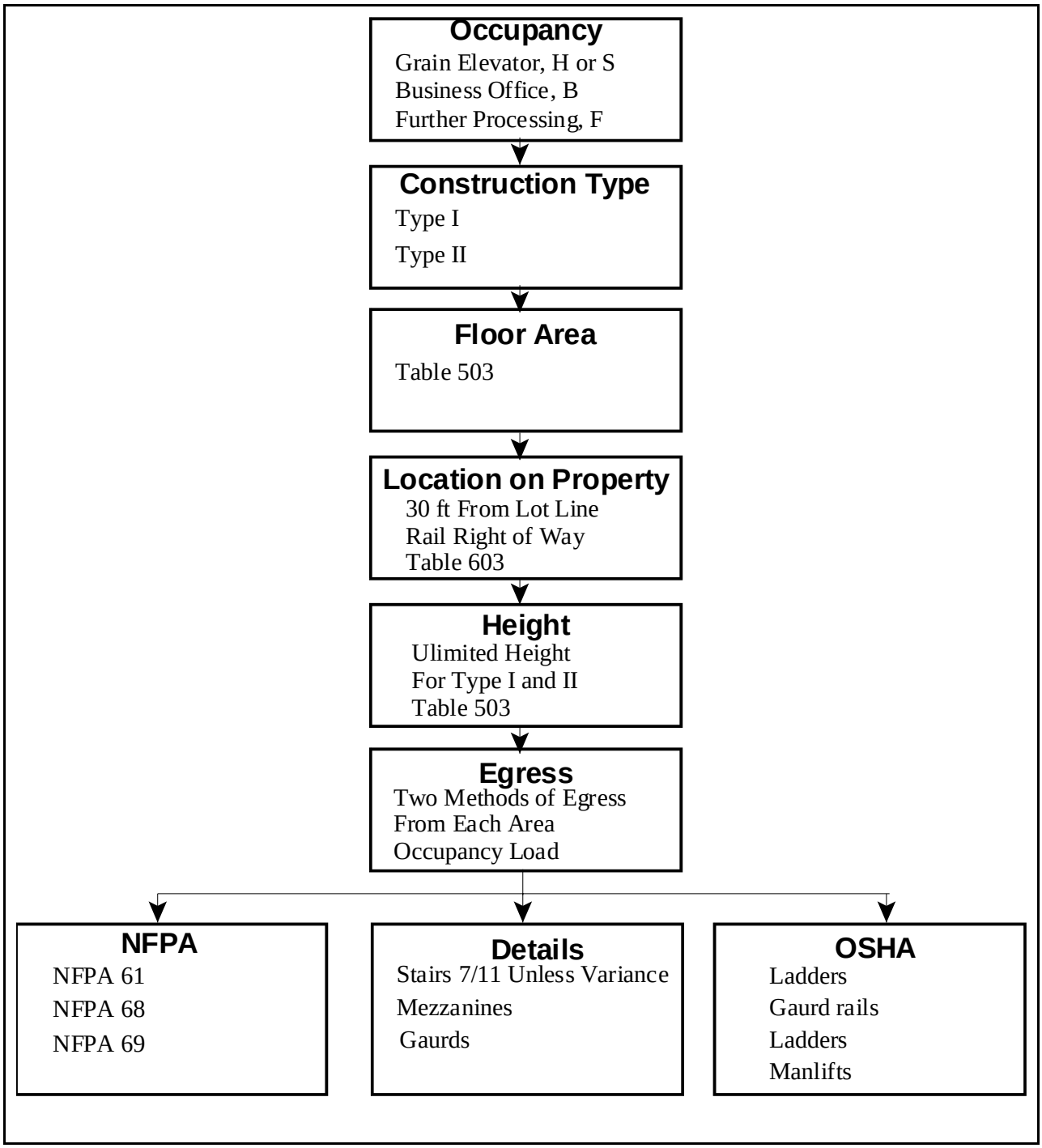

Figure 3. Flow chart of life safety design considerations.

Structural Design Considerations

Typical structural elements of a grain handling facility include: (1) foundations, (2) pits, (3) reclaim tunnels, (4) silo walls, (5) hoppers, (6) roof elements, and (7) equipment towers. Loads on grain elevator facilities are unique and require special attention by the engineer. Because of the specialized design requirements for grain elevator facilities, which are currently undocumented, this section will examine several commonly used design procedures.

Overview of Grain Elevator Loads

Before the actual structural analysis and design is undertaken, the loads on the total system must be determined. Items such as structural tower weights, equipment weights, snow, and floor and roof live loads must be determined. This information can be gleaned from equipment vendors and from the building code documents such as ASCE 7-98 Minimum Design Loads for Buildings and Other Structures (ASCE, 1998). Additionally, bulk solids loadings for grain or other materials must be determined using ACI 313 (ACI, 1997) or ASAE EP 433 (ASAE, 2001).

Table 2 provides bulk solids properties for commonly stored grains in North America. Although many methods exist for the determination of the vertical and lateral loads, the most commonly used equation for bulk solids loading is Janssen's equation:

$$q = \frac{\gamma R}{\mu k}\left(1 - e^{\frac{-YR}{Uk}}\right) \tag{1}$$

Where:

q = vertical pressure (lb/ft^2)

R = hydraulic Radius (ft)

μ= coefficient of friction

k = lateral to vertical coefficient

γ = density (lb/ft^3)

Y = depth of product (ft)

And the lateral wall pressure, p (psf), from bulk solids is given by:

$$p = kq \tag{2}$$

Finally, the following equation gives wall friction, V (psf), from bulk solids

$$V = (\gamma Y - q)R \tag{3}$$

Janssen's equation is dependent on the coefficient of friction of the material, the bulk density, the lateral to vertical pressure coefficient, and the depth of the grain. Janssen's equation represents the static pressure of the grain in a silo. It is necessary to adjust the pressures for the dynamic effects of filling or discharging of the grain. This is commonly done in practice by multiplying the lateral wall pressure by an overpressure factor. Common values for overpressure are shown in Table 3. Recommendations for overpressures vary by country, standard, and material. When the height-to-diameter ratio is less than 1 it is common for the bin or silo to be classified as a shallow. Experience among designers and engineers have shown that the overpressure factors can typically be ignored. It should be noted that shallow bins/bunkers experience impact; therefore, use of impact factors should be considered.

Table 2. Physical properties of grain essential for structural design.

Commodity	Density (lb/ft^3)	Angle of Internal Friction	Effective Angle of Internal Friction	Coefficient of Friction Against Corrugations	Coefficient of Friction Against Concrete	Coefficient of Internal Friction Against Steel
Barley	45 – 54	20	26 – 33	Varies	.46 - .62	.32 - .51
Corn	45 – 54	30	28 – 33	Varies	.46 - .62	.36 - .58
Soybeans	50 – 60	23	25 – 32	Varies	.25	.20
Wheat	48 – 60	20	26 – 33	Varies	.46 - .62	.32 - .58

Table 3. Recommended overpressure factors.

Material/Construction Type	Minimum Over Pressure Factor, C_d	Source
Concrete	1.5, 1.4	ACI 313-97, ASAE (2001)
Smooth Wall Steel	1.35 min, 1.4	Rotter (2002), ASAE (2001)
Corrugated	1.5, 1.4	Rotter (2002), ASAE (2001)

Lateral loads from wind or seismic forces can have an impact on the design of a grain elevator facility. In the latest versions of the IBC and ASAE-7, there are extensive sections for determination of wind and seismic loads for non-building structures. In these documents there is guidance on the distribution of seismic loads on non-building structures that states that the load should be located on the center of mass. On small silos or bins this approach is rational. For larger, taller silos, placing the seismic force through the center of mass of the entire contents is less representative of the seismic response than distributing the load incrementally over the height of the structure. Because of this, the authors recommend that the seismic load be distributed in ten-foot increments over the height of the silo. Although specific requirements for seismic lateral design of silo walls are not in ACI 313 the reader is directed to Chapter 21 of ACI 318 (ACI, 1999) for the seismic requirements of shear walls. Gaylord and Gaylord (1984) contains a number of discussions on lateral load for steel silos.

Finally, there are a number of additional live loads for grain handling facilities. These loads include worker platform loads, movable and fixed equipment loads, temperature cables and many other temporary loads. Table 4 outlines typical conditions that the design engineer must consider.

Foundations

Foundations for grain elevators have a number of unique features that are not common in general building construction because of large loads. These features include the use of mat or raft foundations and ring foundations to support the silo/bin structures above. These foundations may be soil supported or pile supported. Occasionally, a composite soil/pile foundation system may be used. The soil engineering requirements for most grain elevators are demanding and most geotechnical engineers are not familiar with the high pressures and settlements that accompany these rigid structures. The structural engineer designing the facility must be aware of the capabilities of the geotechnical engineers prior to beginning the project.

Table 4. Typical live loads for grain handling facilities.

Area	Uniform Load	Concentrated Load	Comments
Roof Slab	Greater of 50 psf live load and snow load	Actual equipment or tower loads	Can eliminate point load reactions by adding floor beams under reaction point
Roof Beams	Greater of 50 psf live load or snow load	Temperature cable loads. 10 Kips minimum	Make roof beams composite to help with temperature cable loads
Work Floors	100 to 200 psf live loads are typical depending on situation	Equipment reactions should be checked. vibration can be a concern	The engineer should consider the possibility of a grain spill on the floors
Elevated Bin Floor Bottoms	Per modified Janssen's equations	Usually there are none because of the need	Don't forget the sand fill slick coat
Equipment	Usually none	Per equipment vendor see flow diagram for location. Vibration can be a concern	Locate near beam supports to limit effects of punching or additional flexural loads.
Stairs	100 psf	1000 lb point load	OSHA requirements

Common piling types used in grain handling facility include: (1) auger cast piling, (2) steel H piles, (3) caissons, and (4) precast piling. The US Army Corps of Engineers provides guidance on the design and analysis of pile foundations (USACE, 1991). Except for the worst seismic zones, overturning and uplift is not a concern on grouped silos and the weight of the dead and live load of the facility will control the number of and spacing of the piling or the required soil bearing capacity. For single silo structures it is necessary for an engineer to evaluate the overturning forces that result from seismic or wind forces because this can influence the soil or pile design.

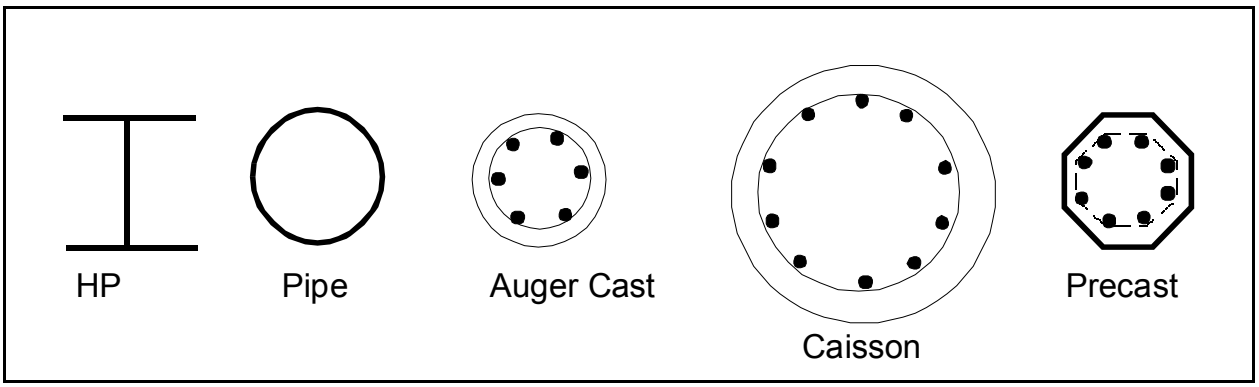

Figure 4. Typical piling types used for grain elevator foundations.

A soil-supported mat slab analysis uses either the rigid slab method or the Finite Element Analysis (FEA). As the name implies, the rigid method involves treating the mat slab as an infinitely rigid body with respect to the distribution of the load for purposes of analysis, thus the applied load is uniform. The rigid analysis is conducted using elastic methods and plate theory (Timoshenko, 1959) combined with superposition. FEA involves the use of soil springs and

plate elements to determine the distribution of loads. The first step is the determination of the subgrade modulus. Typically, the soil engineer will determine the subgrade modulus, but sometimes the structural engineer must estimate the value. Figure 4 shows the commonly accepted relationship between bearing strength and spring stiffness. Other important considerations in mat foundation design are the relative mesh density of the finite elements, shell element formulation, mat structure stiffness, and a cracked or uncracked section. Each of these variables can influence the distribution of forces through the mat, thus the engineer must be aware the effects (Ulrich, 1995). After the analysis is conducted using either method, the foundation must checked at critical sections for the effects of flexure and one way and punching shear as defined in ACI 318 (ACI 1999).

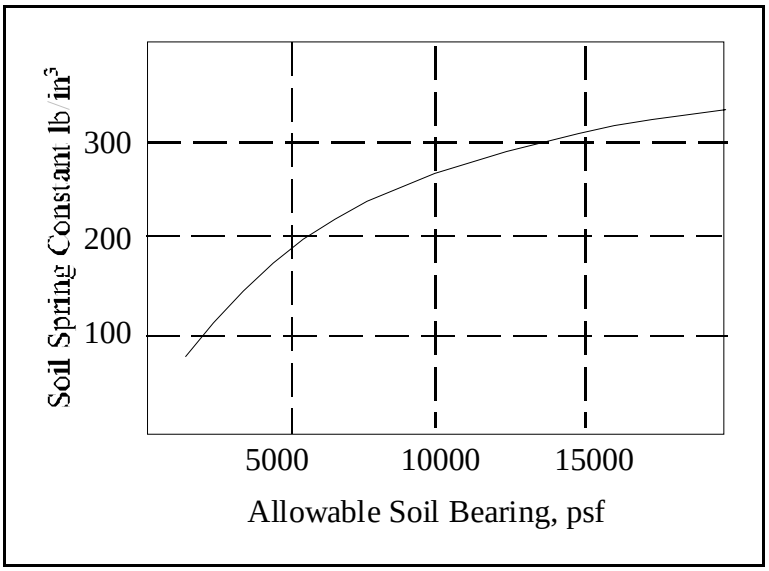

Figure 5. Relationship between soil bearing capacity and soil spring constant (PCI Handbook, 2003).

Pits and Tunnels

Boot pits and tunnels form the underground portion of the reclaim system for a grain elevator facility (figure 1). Because they are directly below or adjacent to the mat slab, there are high roof pressures and/or lateral surcharges on the walls from the grain pressure above. These pressures are defined by Janssen's equation (ACI, 1997) and can total into the thousands of pounds per square foot. Because of this, these elements must be designed to carry these loads. Tunnels are comprised of slabs and walls, and must meet the provisions of ACI 318 (ACI, 1999) for walls and slabs. Figure 6 shows a typical reclaim tunnel section for a grain elevator with surcharges. For the detail shown, the walls and slab elements are pin connected. It is possible to have continuity at the joints with the addition of corner steel. Figure 7 shows a typical horizontal section of a boot pit. Depending on geometry, boot pit walls can span either horizontally or vertically. Deeper boot pits will usually span horizontally. When loads are too high, the span can be broken up using a vertical pilaster. In the analog shown in Figure 7, continuity in the corners is used to reduce the absolute magnitude of the bending moment. Boot slabs are designed as two-way plate elements using two-way plate formulas from Timoshenko (1959). Similar to tunnels, the elements of the boot pit must meet the design requirements of ACI 318 (ACI 1999) for slabs and walls.

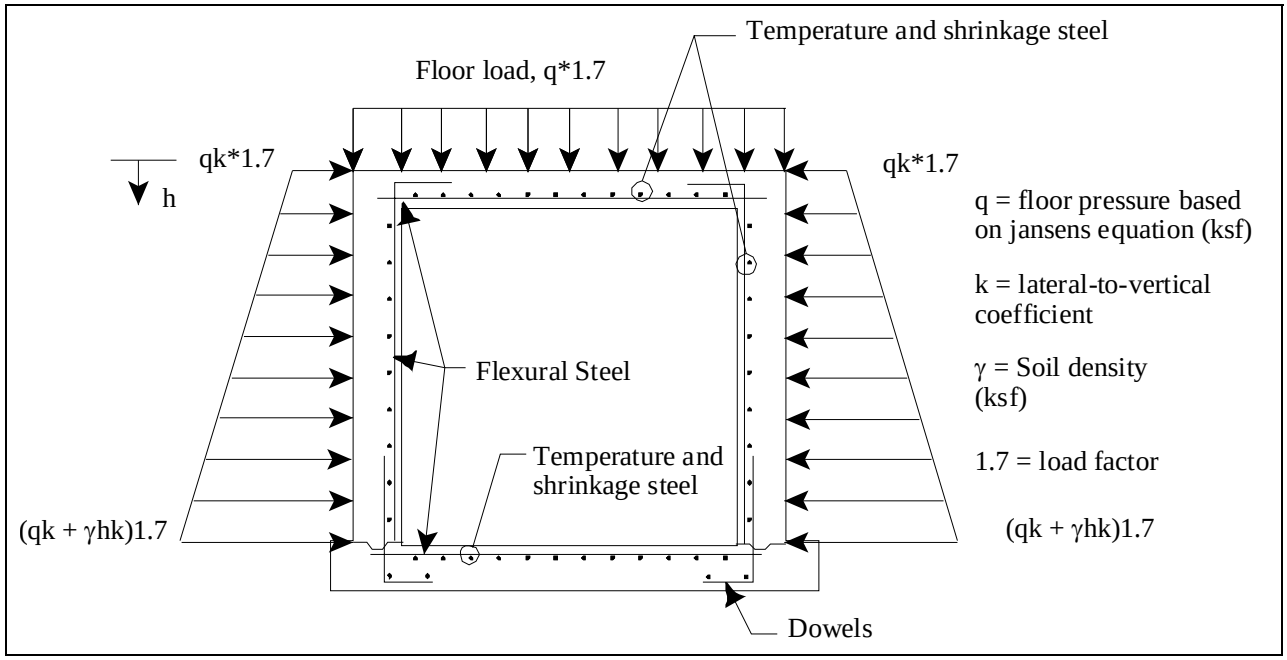

Figure 6. Typical tunnel reclaim tunnel loadings.

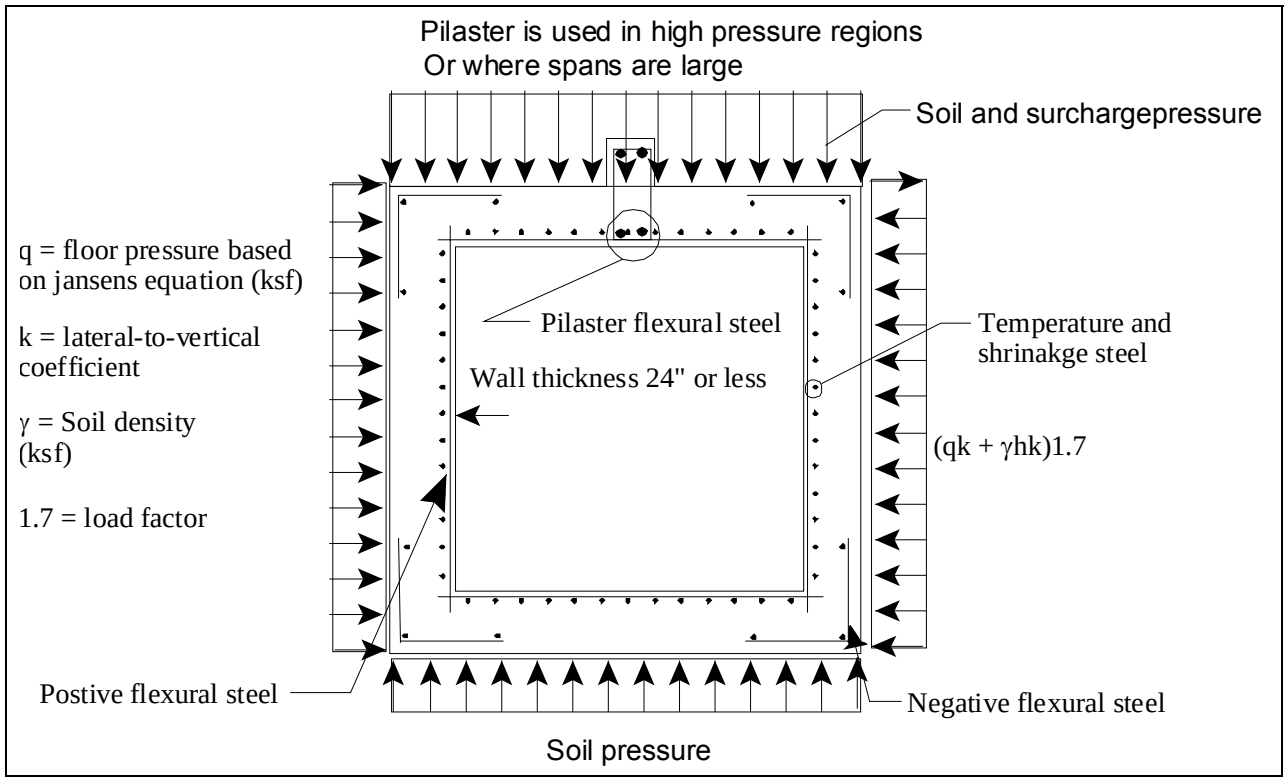

Figure 7. Typical horizontal boot pit section.

Silo and Bin Walls

Most silos are circular and the forces are determined using the hoop pressure equation (ACI,, 1997). Silos with multiple sides, such as rectangular bins, are subject to bending, shear, and axial forces that result from static and dynamic forces developed in the bin. Pocket bins and interstice bins experience either axial compression or tension and shear, and bending forces and often behave like arches. Guidelines for handling bending and shear on silo walls are discussed in Gaylord et al (1997). Ideally, most bins should be designed for concentric discharge. Concentric discharge is defined as where the discharge point in the bin coincides with the geometric center of the mass of grain. Hoop tensions are developed from concentric discharge and are defined by the following equation:

$$T = \frac{pD}{2} \tag{5}$$

Where

T = hoop tension (lbs)

p = lateral pressure defined in loads section (psf)

D = Diameter (ft)

When the discharge point does not coincide with the centroid of the grain mass, bending and shear forces must be resisted by the silo walls. In North America, there are no officially endorsed methods for calculating forces due to eccentric draw off. Most engineers use a method that was proposed in the 1977 version of ACI 313 (ACI, 1977). This method involves increasing the hoop steel by fictitiously increasing the uniform lateral pressure in the silo. This method, however, does not give the engineer a method to calculate the bending forces in the silo wall. It is commonly used by engineers who design concrete silos. This method is given by the following basic equation where the design pressure is given by:

$$p_{des} = C_d\, p_{st} + p_{ecc} \tag{6}$$

Where

P_{des} = design lateral pressure (psf)

C_d = over pressure factor (defined in table 3)

P_{st} = static lateral pressure defined in equation 2 (psf)

for $H \leq D$,

$$p_{ecc} = 1.25\, p_{st} \tag{7}$$

And for $H \geq D$

$$p_{ecc} = 1.25\, p_{st} \frac{(Y - D)}{(H - D)} \tag{8}$$

Where:

P_{ecc} = eccentric lateral pressure (psf)

Y = effective depth of bulk solid (ft)

D = silo diameter (ft)

H = silo height (ft)

A more advanced method, which is being used in Europe, was developed by Rotter (2001). This method involves a three-part calculation. The first part involves flow channel geometry definition. The second involves calculation of pressures within the flow channel, and finally, the third part involves calculating pressures outside of the flow channel. At this point, the pressures are determined along the height of the silo and bending, shear, and axial forces are determined using analysis methods.

Flow channel geometry definition is given by the following equations:

$$r_f = r(1 - E(E + \eta[1 - E])) \tag{9}$$

$$E = \frac{e_o}{r} \tag{10}$$

$$\eta = \frac{\mu}{\tan \phi_i} \tag{11}$$

Where:

r_f = flow channel radius (ft)

r = radius of the circular silo (ft)

μ = wall friction coefficient

ϕ_I = effective angle of internal friction (degrees)

e_o= eccentricity (ft)

E = ratio of flow channel eccentricity to silo radius

η = ratio of wall friction coefficient to tangent of the angle of internal friction

Additional flow channel geometric properties are defined by the following equations:

$$\cos \theta_c = \frac{r^2 + e_o^2 - r_f^2}{2re_0} \tag{12}$$

$$U_{wf} = 2\theta_c r \tag{13}$$

$$U_{ws} = 2(\pi - \theta_c)r \tag{14}$$

$$U_{sf} = 2r_f(\pi - \psi) \tag{15}$$

$$A_f = (\pi - \psi)r_f^2 + \theta_c r^2 - rr_f \sin(\psi - \theta_c) \tag{16}$$

$$A_s = \pi r^2 - A_f \tag{17}$$

$$\sin \psi = \frac{r_f}{r} \sin \theta_c \tag{18}$$

Where the additional variables are defined as:

θ_c = circumferential coordinate at edge of eccentric flow channel (degrees)

U_{wf} = arc length of contact between the flow channel and wall (ft)

U_{ws} = arc length of the contact between static material and the wall (ft)

U_{sf} = arc length of contact between the flow channel and static solid (ft)

A_f = cross sectional area of the flowing channel (ft^2)

A_s = cross sectional area of stationary material (ft^2)

Ψ = angle in eccentric flow channel

Rotter (2001) cites that at least three basic flow geometries should be investigated, e_0, $(r+e_0)/2$, and $e_o/2$

The pressures in the flow channel are calculated using the following relationships:

$$p_{hfe} = p_{hfo}\left(1 - e^{\frac{-y}{z_{of}}}\right) \tag{19}$$

$$p_{hfo} = k\gamma z_{of} \tag{20}$$

$$z_{of} = \frac{1}{k}\left(\frac{A_f}{U_{of}\,\mu + U_{sf}\,\tan\varphi_i}\right) \tag{21}$$

Where:

P_{hfe} = wall pressure in flowing zone of eccentrically discharging silo (psf)

P_{hfo} = horizontal at great depth after filling (i.e. asymptotic value) (psf)

k = lateral to vertical coefficient

γ = density of stored material (lb/ft^3)

μ = coefficient of friction for wall

φ_i = angle of internal friction (degrees)

y = depth of grain (ft)

z_{of} =Janssen reference depth for flowing zone in eccentrically discharging silo (ft)

Pressures in the static zone are given by:

$$p_{hse} = \gamma k z_{os}\left[1 + w + wue^{\frac{-y}{z_{of}}} - (1 + w + wu)e^{\frac{-y}{z_{os}}}\right] \tag{22}$$

$$u = \frac{z_{of}}{z_{of} + z_{os}} \tag{23}$$

$$w = \left(\frac{A_f}{A_s}\right)\left(\frac{U_{sf}\,\sin\varphi_i}{U_{ws}\,\mu + U_{sf}\,\tan\varphi_i}\right) \tag{24}$$

$$z_{os} = \frac{1}{k}\left(\frac{A_s}{U_{ws}\mu}\right) \tag{25}$$

Where:

p_{hse} = horizontal pressure in static zone of eccentrically discharging silo (psf)

u = constant

w = constant

z_{os} = Janssen reference depth for static zone in eccentrically discharging silo (psf)

Flow channels cause variable pressures in bin structures. Because of this, the engineer should be careful when designing metal bins because there is little capacity to carry bending moments. Non-uniform pressures cause two-way plate bending in steel storage structure walls, which may necessitate the extra reinforcement. In concrete silos there is significant bending capacity and for design purposes it is commonly treated as one-way horizontal bending that requires extra hoop steel. The off direction or vertical bending is neglected. Shear forces must also be checked at critical sections.

Vertical wall pressure can be significant for plain and corrugated steel bin walls. The vertical compression capacity for corrugated steel bins is limited. Unlike concrete bins, the vertical capacity of the silo walls is easily exceeded. On the other hand, vertical compression on concrete silo walls is rarely exceeded by the frictional forces from the grain. The most common method for the calculation of vertical wall allowable stress of smooth steel walls is the boardman formula (Gaylord and Gaylord, 1984):

$$f_a = 2{,}000{,}000\frac{t}{R}\left(1 - \frac{100t}{3R}\right) \tag{26}$$

Where:

f_a = vertical wall allowable stress (psi)

t = tank wall thickness (psi)

R = tank radius (inches)

For concrete walls, ACI 313 (ACI, 1997) simply states that keeping vertical pressures below the following is sufficient for design

$$P_{nw} = 0.55\phi f_c^{'} \tag{27}$$

Where:

P_{nw} = allowable wall pressure (psi)

φ = strength factor

f'c= concrete compressive strength (ksi)

Corrugated steel walls do not have significant vertical load capacity and should be designed using vertical stiffening elements. These are typically designed using design specifications published by AISC (AISC, 1989). Other sources of design information for steel tanks include the American Petroleum Institute documents (API, 1998 & 2002). The reader should also be made aware that wall traction forces can vary for silos with eccentric discharge. For details the reader is referred to Rotter (2001)

Floors

Elevated floors in grain handling facilities support equipment or grain. These floors tend to be heavily loaded. Elevated slab live load pressures are determined using Janssen's equation. Elevated floor slabs in concrete grain elevators are typically keyed into the walls. The analysis of the walls is conducted using two-way plate theory (Timoshenko, 1959) or one way slab theory (ACI, 1999). Occasionally, the floor will hold grinding or other large equipment that must be designed using vibration theory.

Hoppers

Bin bottoms are either formed by the foundation in combination with bin fill or a hopper. Bin fill is a sand cement mixture used to form hoppers at grade. It is formed into a sloping surface to help discharge grain. Suspended hoppers in silos are typically conical in shape. Cone hoppers can be constructed from either steel or concrete. Figure 8 shows a typical silo configuration for a grain silo. Typically, hoppers are designed using membrane or theory/large deflection theory. The equation for meriodal forces (lbs) in a conical hopper under uniform load is given by:

$$F_m = \frac{qD}{4\sin\alpha} + \frac{W}{\pi D\sin\alpha} \tag{28}$$

Where:

q = uniform pressure at top of hopper (psf)

D = diameter at top of hopper (psf)

W = weight of stored material in hopper (lbs)

α = angle of hopper measured from horizontal (degrees)

Similarly the equation for tangential force (lbs) is given by:

$$F_t = \left(\frac{p\sin^2\alpha + q\cos^2\alpha}{2\sin\alpha}\right) \tag{29}$$

Where:

p = lateral pressure (psf)

q = vertical pressure (psf)

α= angle of hopper measured from horizontal (degrees)

D = diameter (ft)

Other factors that must be accounted for in the design of the hopper include switching forces at the hopper and wall interface if the discharge is mass flow. Details about the calculation of mass flow forces are given in Gaylord and Gaylord (1984) and ACI 313 (ACI, 1997). The engineer will also need to size a suitable compression ring at the juncture too. This is computed using the horizontal reaction from the cone hopper.

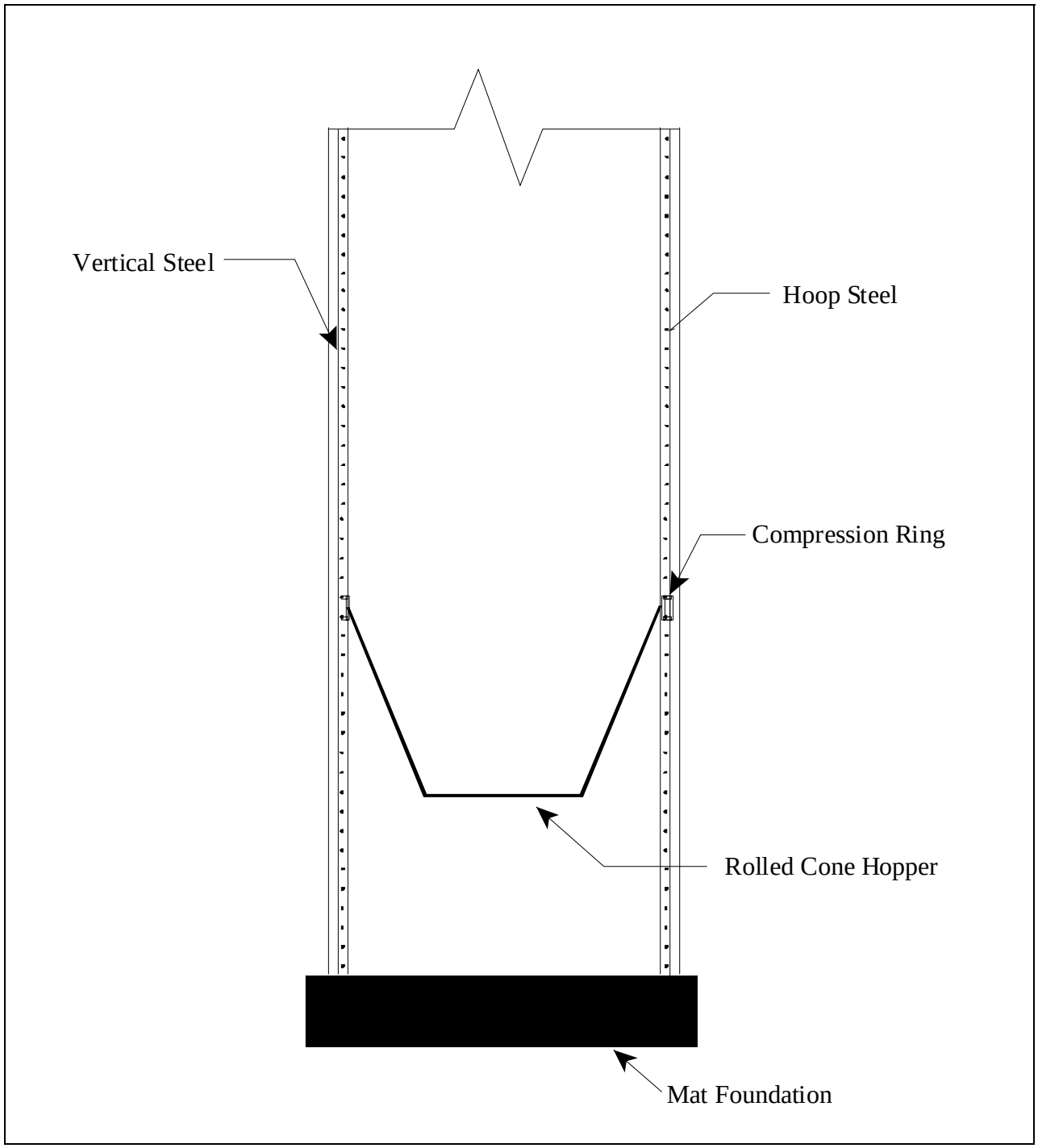

Figure 8. Silo wall section showing the walls, hopper and foundation.

Roof Design

There are three kinds of roofs on grain handling facilities, the conical roof, the rafter supported conical roof, and the flat roof. All metal silos use conical roof systems. Concrete grain elevators typically use flat concrete roof system supported on beams. For conical steel bin roof systems engineers should be warned that ASCE-7 lacks a snow load calculation for unbalanced snow loads, which could be critical for design. For a conical roof under vertical uniform load along length Gaylord and Gaylord (1984) give the formula as:

$$N_1 = -\frac{ws}{2\sin\varphi} \tag{30}$$

$$N_2 = -\frac{ws\cos^2\varphi}{\sin\varphi} \tag{31}$$

Where:

N_1 = longitudinal force (lbs)

N_2 = meriodal force (lbs)

w = load per foot along length (psf)

s = length along cone (ft)

Φ = cone hopper angle from horizontal

Point loads from unbalanced snow and live loads, catwalks, conveyors or other miscellaneous equipment may necessitate a formal finite element analysis. In rafter type roof construction, the radially spaced, inclined beams span from the outer walls of the bin or tank to a center compression ring at the peak of the bin or the silo. Corrugated sheeting spans from rafter to rafter. Sometimes the cladding and the rafters are incorporated into a single element. On concrete slip form silos, most concrete roof slabs consist of a 5 to 6 inch thick cast in place concrete slab supported by steel beams. A slight slope on the roof of about a ¼ to 1/8 inch per foot running each way in the narrow direction of the elevator to shed water is added. For larger diameter silos, it is necessary to pre-camber the roof beams at least equal to the dead load and one half of the roof live load. In modern grain elevator construction, temperature cables are attached to the roof beams. It is therefore important to design the beams for these loads. It is common to make the roof beams composite with the floor beams. An elastomeric roof coating is applied to concrete roofs to provide a more durable surface.

Equipment Support Towers

Equipment towers on top of grain elevators support distribution and cleaning equipment, as well as spouting. Tower heights are dictated by the minimum flow angles of the material being distributed by the spouting to the storage bins. In addition there are ladders, ladder cages, worker access platforms, and drive torque forces that must be resolved into the structure.

Most structural towers are of braced frame construction with “X”, “K”, “V”, and other admissible forms of structural bracing. The engineer is reminded to review the requirements of the building relating to bracing in seismic zones, as some bracing configurations are not allowed in the more restrictive seismic design categories (ICC, 2000). Generally, the wind load for the tower must be checked for the two orthogonal directions, plus the two diagonal directions and the wind load pressure is then determined for the projected face of the tower. Tower anchorage is often challenging on slip form silo walls because the towers are tall and the anchorage often occurs

on narrow silo walls that limit the breakout cone of the concrete. One way to work around this is to ensure that there is special supplemental steel to intersect the plane of rupture on the wall.

Summary

This paper summarizes design procedures related to the construction and planning and operation of grain elevators. In particular, the life safety, planning, and structural provisions were discussed. Standards, procedures and methods of design and construction where discussed, including state of the art procedures. Both, engineers and educators should find this paper useful.

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