Cause of Damage and Failures in Silo Structures

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Abstract: Silos are special structures subjected to many different unconventional loading conditions, which result in unusual failure modes. Failure of a silo can be devastating as it can result in loss of the container, contamination of the material it contains, loss of material, cleanup, replacement costs, environmental damage, and possible injury or loss of life. Silo damage and failures that occurred in different regions of the world are presented in the paper using illustrative photos. Also provided are a review and discussion of the common or spectacular silo failures due to explosion and bursting, asymmetrical loads created during filling or discharging, large and nonuniform soil pressure, corrosion of metal silos, deterioration of concrete silos due to silage acids, internal structural collapse, and thermal ratcheting. Silo damage and failures from several earthquakes are also presented.

DOI: 10.1061/(ASCE)0887-3828(2009)23:2(65)

CE Database subject headings: Silos; Cylindrical tanks; Storage facilities; Damage; Failures.

Introduction

Containers used for storing bulk solids are usually called bins, bunkers, silos, or tanks. Although there is no generally accepted definition for these terms, shallow structures containing coal, coke, ore, crushed stone, gravel, and similar materials are often called bins or bunkers, and tall structures containing materials such as grain and cement are usually called silos (Li 1994). This paper will focus on the failure of silo structures, which have been widely used in many industries including chemical, mining, electric power generation, agriculture, and food processing.

Most silos are steel or reinforced concrete cylindrical structures built on mat foundations. Sometimes they could be elevated and supported by frames or reinforced concrete columns. The design of silos is primarily governed by the type and properties of the stored material. As the density, flow and friction properties of grains, cement, coal, carbon black, and other bulk materials vary widely, the loads applied on a silo structure and the associated load carrying system are different from the traditional building type structures. As a result, silos are designed and evaluated as special structures. Currently, the ACI 313 document (ACI 1997) is the only guideline published in the United States specifically for the design and construction of silos and similar storage structures.

The walls of the silos are typically subjected to both normal pressure and vertical frictional shear or traction produced by the material stored inside the silo. The magnitude and distribution of both shear and normal pressure over the height of the wall depend on the properties of the stored material and whether the silo is being filled or discharged. Other potential loads, including seismic and wind loads, stresses created by temperature difference between the silo wall and the stored bulk solids, potential expansion of the stored material, and differential settlement of the foundation or support columns, should also be considered during the design process.

The failure of a silo structure usually leads to catastrophic collapse of the entire silo. This is largely due to lack of sufficient structural redundancy in most cylindrical shell structures, as well as lack of alternate load path to redistribute stresses and forces within the structure after a local failure or damage occurs. The ensuing complete structural failure results in not only loss of contained material but also loss of life in some cases. The silo failures are typically brittle and sudden, sometimes caused by an explosion. The failed silo structure may also fall onto the adjacent barn or industrial facilities, resulting in an additional loss, and possibly injuring or killing people and/or animals. The main objective of this study is to present silo damages and failures and to discuss their causes. Damage and failures that occurred in silos in different regions of the world are presented and discussed.

Silo Damage, Loads, and Failures

Silos fail with a frequency much higher than the rate of failure of other industrial structures. Although statistics are not available, hundreds of industrial and farm silos, bins, and hoppers experience some degree of failure each year (Carson 2000). When a silo fails it can be devastating, in more ways than one including: loss of the container, contamination of the material it contains, loss of material, cleanup, replacement costs, and most importantly possible injury or loss of life (Lewis 2006). Furthermore, the designer and contractor face possible litigation because of their liability exposure. Consequently, the direct and indirect costs associated with failure of a silo are in most cases considerably large.

Silos are subjected to many different static and dynamic loading conditions mainly due to unique characteristics of the stored materials. As each bulk material behaves differently under various

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Note. Discussion open until September 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on October 8, 2007; approved on June 6, 2008. This paper is part of the ***Journal of Performance of Constructed Facilities***, Vol. 23, No. 2, April 1, 2009. ©ASCE, ISSN 0887-3828/2009/2-65–71/$25.00.


(a) (b)

Fig. 1. View of silo in France: (a) before accident; (b) after explosion (Mavrot et al. 2003). (This figure was published in the *Journal of Loss Prevention in the Construction Industries*, Vol. 16, by G. Mavrot, I. Sochet, P. Bailly, and M. Moisescot, "Silo vulnerability: Structural aspects," 165–172. Copyright Elsevier, 2003.)

temperatures, and during filling and discharging, it is difficult to determine the magnitude and distribution of loads and the corresponding failure modes. In addition, in many cases simplified analysis procedures are not available to capture the static or dynamic response of the entire silo, as in analysis and design of conventional frame structures. As a result, typical silo design or analysis usually requires in-depth analysis or finite-element analysis of the contained material-silo-foundation system. The main causes of silo failures and collapse are reviewed and discussed below.

Explosion and Bursting

Internal explosions or bursting failures mostly occur in silo structures, which are rare in traditional frame structures as they are typically not exposed to such loads. Theoretical studies of flow pressures on silos suggest that the occurrence of very high "switch" pressures on limited zones of the wall are likely to cause the bursting failure of the cylindrical shell of many silos (Li 1994). Some silos are subjected to the explosion of methane, which is produced by fermentation of the stored forage or fodder. Cases of bursting or explosion are, nevertheless, rather rare. Kieselbach (1997) reported bursting of a large silo on a farm, which resulted in considerable environmental damage and economic loss due to misuse of the silo for vegetable slurry instead of for feed for livestock, and overfilling of the silo. A cellular reinforced concrete grain storage facility failure occurred in France in 1997 and caused 11 deaths (Fig. 1). The cause of the silo failure and collapse was an internal explosion and bursting (Mason and Lechaudel 1998).

Filling and Discharging

Asymmetric flow patterns caused by ratholes, preferential flow channels, or asymmetric loading patterns created by bulk material during filling or discharging can cause silos to dent, buckle, and even collapse. As shown in Fig. 2, collapsing ratholes and bridges can also lead to silo failure problems (Marinelli 2004). Fig. 3 shows another example of complete structural failure during standard operation (Piskoty et al. 2005). The 16-year-old silo was completely filled with 700 t of grain. After the release of approximately 15 t of corn, the emptying process was interrupted for a visual inspection. Shortly afterward the silo suddenly burst (Fig. 3).

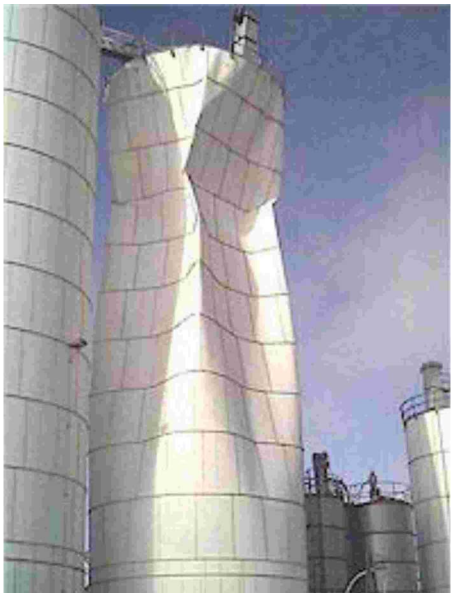


Fig. 2. Damage to upper part of silo due to flow problems (Marinelli 2004, with permission)

Soil Conditions

Silos are relatively slender structures with a small floor area or diameter compared with their height. As a result, considerably large axial stresses are produced at the base of the structure due to the weight of the bulk material and structure. The supporting soil is typically subjected to uniform compressive pressure due to applied gravity loads. The foundation of silos should be designed more carefully than that for standard building structures. For example, nonuniform placement of bulk material during filling can result in nonuniform pressure distribution at the base and cause

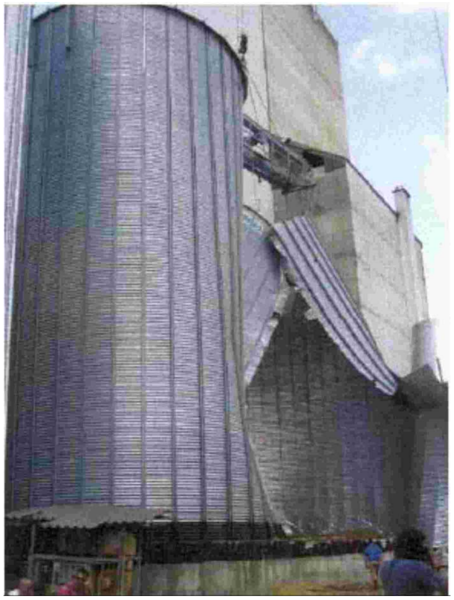


Fig. 3. Burst silo had fallen onto adjacent silo on left causing collateral damage (Piskoty et al. 2005). (This figure was published in *Engineering Failure Analysis*, Vol. 12, by G. Piskoty, S. A. Michel, and M. Zgraggen, "Bursting of a corn silo—An interdisciplinary failure analysis," 915–929. Copyright Elsevier, 2005.)

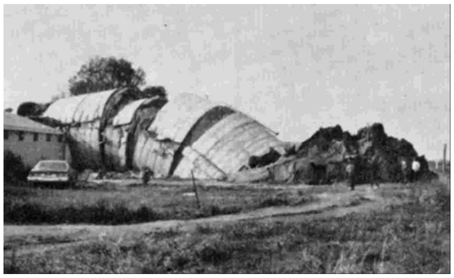


Fig. 4. Failure of 2,500-t capacity silo damaging adjacent barns (Bozozuk 1976, ASCE)

problems. When the vertical load from the weight of the stored material is off center, the pressure bulb under the silo will be distorted. Lateral loads due to earthquakes or strong winds can also produce similar effects. The local overstressing of the soil beneath the foundation may then cause tilting, relative settlement, and even collapse.

Most foundation failures in clay soils occur when a silo is quickly loaded for the first time (Fig. 4). As the filling proceeds, the loads are applied and carried by both the soil skeleton and the pore water contained within the voids of the clay. The pressure generated in the pore water tends to reduce the friction between the soil particles and hence decrease the shear strength of the soil. If the available shear strength is greater than the applied shear stresses at the end of loading, the structure will be stable. With time the excess pore-water pressure dissipates, the soil consolidates and gains strength, and the structure becomes stable for the subsequent loading (Bozozuk 1976).

The soil underneath the two adjacent grain silos built in the Red River Valley in Canada did not have sufficient strength to resist the applied gravity loads (Fig. 5). Bozozuk (1972, 1976) reported that the silos were built on Lake Agassiz clay and were too close so that the "pressure bulbs" under the foundations overlapped. This caused larger stresses and, in turn, larger settlements under the parts of the ring foundations where they were closer to each other. The end result was tilting, touching, and eventual structural failure of the silos. If a group of bins are constructed together to form a cellular structure, there is a potential for the individual stress bulbs to overlap in the two orthogonal directions. Consequently, the ground is exposed to amplified stresses in a larger area under the silo structure. In 1913, the group of 65 grain bins shown in Fig. 6 started to tip over. The newly built silo was loaded with over 1 million bushels of wheat. The structure continued to sink slowly for over 12 h until it was at angle of 30° from vertical but still intact (Clerkin 2004). First, the wheat was emptied from the bins to bring the structure back into a vertical position. After tunneling underneath the structure, new foundations were built on bedrock. The structure was then pushed back into its current vertical position. The silo is still in use today.

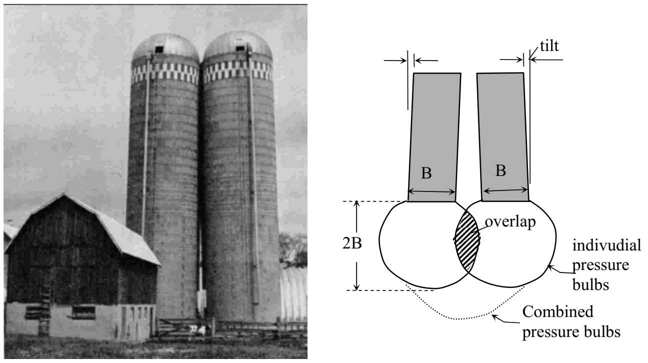
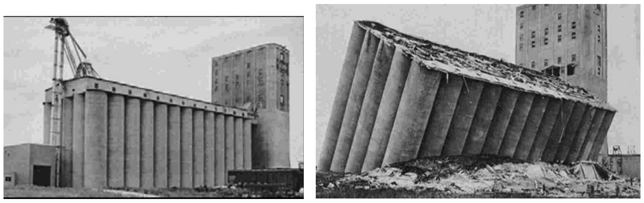


Fig. 5. Leaning twin silos due to nonuniform settlement in zone of overlapping pressure bulbs (Bozozuk 1976, ASCE)



(a) (b)

Fig. 6. Sinking of grain silos due to soil problem: (a) before accident; (b) after sinking (Clerkin 2004)

Corrosion

It is well known that if preventive measures are not taken, corrosion causes deterioration of the metal components of structures. Steel silos are especially susceptible to corrosion and subsequent deterioration and failure. Fig. 7 shows two silos which were damaged and failed as a result of corrosion. Such failures indicate the importance of frequent regular inspections for the structural integrity of metal silos.

Internal Structure Collapse

In 2001, the base of a 18 m diameter silo became unstable and one employee died due to partial collapse of a structure inside the silo (Fig. 8). The top two thirds of the silo had 1,400 t of coal and the bottom third contained equipment for crushing and blending coal before it is fed onto a conveyor and sent to the plant's boiler. The silo was used to store and blend coal for use in the power station's 66-MW fluidized bed generating unit. The employee was believed to have been in his work area in the bottom of the silo when the coal and machinery plummeted to the bottom after the internal structure collapsed (Kazas 2001). This accident shows that for life safety, whenever possible, the machinery and employees should not be inside a silo while the bulk material is stored in the upper portions of the silo.

Deterioration

Concrete silos deteriorate, as shown in Fig. 9, if they are not properly maintained. Silage acids cause most of the deterioration problems in conventional cast-in-place and precast concrete silos.

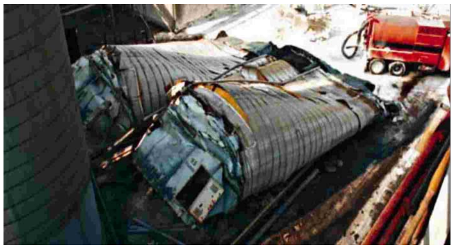


Fig. 7. Views of storage silos collapsed due to corrosion (Photograph by Steven A. Elver, STS-AECOM; Hertlein 2007, with permission)

Fig. 8. View of external damage at MEA coal silo (Kazas 2001, with permission from Morgantown Energy Associates Plant)

The rate and severity of the deterioration depend on a number of factors such as the silo size, moisture content of the ensiled material, and the amount of protection provided over the concrete. Larger silos are more prone to acid deterioration than smaller silos due to the increased horizontal pressure. When moist plant material is placed in a silo it goes through the ensiling process which produces silage acids, namely lactic and acetic. These acids, when they come into contact with concrete silo walls, react with the Portland cement matrix that binds the aggregates together, causing strength decrease to an ever-increasing depth with time. Ensiling highly moist material leads to a greater degree of fermentation and, in turn, a higher level of acid production. This results in accelerated concrete deterioration. Silage acids can decrease the strength of a concrete silo wall to the point where the vertical load on the wall will cause the wall to fail by crushing (Bellman 1996).

Thermal Ratcheting

The silo shown in Fig. 10 collapsed in 1996 in southwestern United States. The collapse occurred at night and the silo was neither being filled nor emptied at the time of the accident. The forensic investigation conducted by Jenike and Johanson revealed that the silo was underdesigned and did not identify or account for a phenomenon called thermal ratcheting. The walls of metal silos expand during the day and contract at night as the temperature drops. If there is no discharge taking place and the material inside the silo is free flowing, it will settle as the silo expands. However, the material cannot be pushed back up when the silo walls contract, so it has to resist the contraction, which in turn causes increased tensile stresses in the wall. The effect is repeated each day and eventually leads to failure of the wall (Carson 2000).

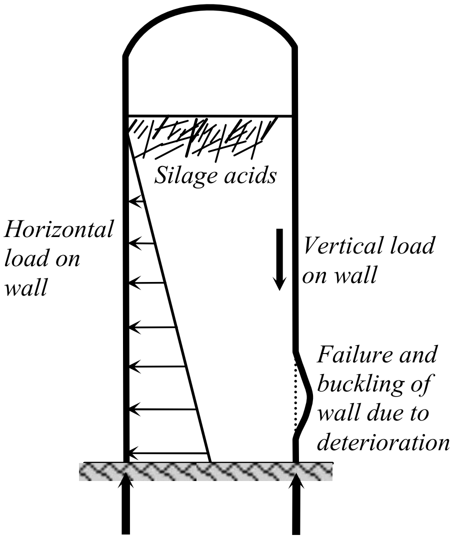


Fig. 9. Common silo deterioration due to silage acid action

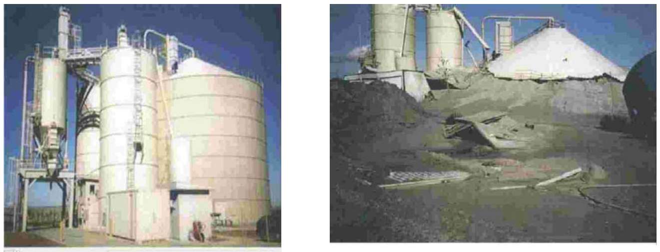

(a) (b)

Fig. 10. Silo failure due to thermal ratcheting: (a) before failure; (b) after collapse (Carson 2000, with permission from Jenike and Johanson, Inc.)

Earthquakes

A number of representative silos that were damaged or collapsed during recent earthquakes around the world will be presented in this section. Possible causes of failures and potential measures to prevent damage will be discussed. Earthquakes frequently cause damage and/or collapse in silos resulting in not only significant financial loss but also loss of life. For example, during the 2001 El Salvador earthquake three people lost their lives as a result of a silo failure (Mendez 2001).

An earthquake ground motion has three components resulting in structural loads in the vertical and two horizontal directions. The effect of vertical seismic loads on the relatively heavy silo structures is usually small, whereas the effect of lateral loads can be significant especially on the taller silos containing heavier material. The magnitude of the horizontal seismic load is directly proportional to the weight of the silo. As the silo height increases the height of the center of mass of the silo structure also increases. Assuming the horizontal seismic load is applied roughly at the center of mass, the moment arm for the lateral load and the corresponding bending moment at the base increase. The increased bending moment then results in nonuniform pressure distribution at the bottom of the silo, which can be significantly larger than the pressure caused by the gravity loads. Earthquakes can also cause damage in the upper portion of the silo if the material contained can oscillate inside the silo during the earthquake. The lateral loads due to material flow and lateral seismic loads must be considered simultaneously if the material can oscillate.

October 3, 1974 Lima, Peru Earthquake

The 8.1 magnitude earthquake occurred 80 km southwest of Lima. The tremor killed 78 and injured several thousand people. During this earthquake, a large grain elevator in the port area of Callao lost its headhouse which fell from the tops of the silos and embedded itself in the adjoining pier (Fig. 11). It was reported that this elevator suffered damage earlier in the 1970 Peru earthquake and was considered unsafe (Moran et al. 1975). This is

Fig. 11. Partial collapse of grain silo during 1974 Lima, Peru earthquake (USGS 1974)

a good example of silo damage resulting from failure of a secondary structure or machinery improperly attached to the silo structure.

March 2, 1987 Edgecumbe, New Zealand Earthquake

The earthquake that struck Edgecumbe, New Zealand on March 2, 1987 had a magnitude of 6.1 and a focal depth of 6 km. This was one of the strongest and most damaging earthquakes to hit New Zealand in recent history. At Bay Milk Products facility in Edgecumbe, huge stainless steel milk silos collapsed, spilling thousands of liters of milk. Two milk storage tanks were thrown on their sides, as shown in Fig. 12.

December 7, 1988 Spitak, Armenia Earthquake

On December 7, 1988, at 11:41 a.m. local time, a magnitude 6.9 earthquake shook northwestern Armenia. Fig. 13 shows the east end of the granary in the flour mill complex east of Spitak. Grain can be seen spilling out of the collapsed concrete shear-wall structures in the foreground. In the background are cast-in-place concrete grain silos. Most such silos had no or only minor damage during the earthquake. However, overall losses at the flour mill complex were large (NGDC 1988). It should be noted the silo structure that failed during this earthquake was noncylindrical, however its height was comparable to that of the nearby undamaged cylindrical silos.

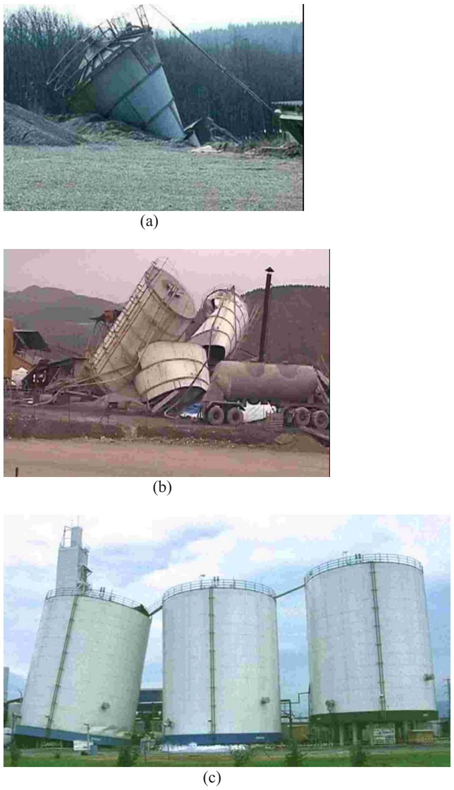
Fig. 12. Collapse of stainless steel milk silos during 1987 Edgecumbe, New Zealand earthquake (CAE 2007, with permission)

Fig. 13. Damaged grain storage complex and spilled out grains due to 1988 Spitak, Armenia earthquake (Photograph by C. J. Langer; JAMA 2007)

August 17, 1999 Kocaeli and November 12, 1999 Duzce, Turkey Earthquakes

The 7.4 magnitude Kocaeli and 7.2 magnitude Duzce earthquakes occurred in northwestern Turkey within 3 months in 1999. Structures in many cities such as Duzce were affected by both earthquakes. For example, the cement silos shown in Figs. 14(a and b) survived the first earthquake but collapsed during the November 12, Duzce earthquake. Although not reported, the August 17 earthquake might have caused some damage earlier. The silos were located near a highway construction site within a very short distance from the fault line ruptured during the second earthquake, and 5 km away from the epicenter of that earthquake.

The three identical liquefied gas storage tanks shown in Fig. 15 were located near the city of Izmit and were built in 1995.



(a)

(b)

(c)

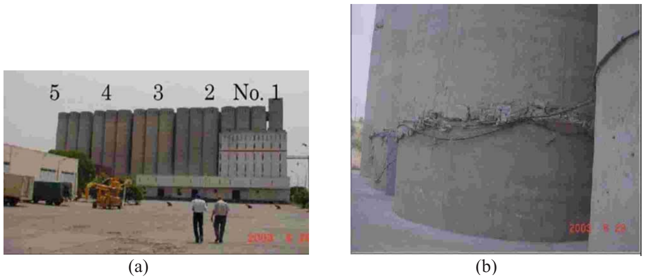
Fig. 14. Silos collapsed during 1999 Duzce, Turkey earthquake: (a) Xiao and Yaprak (1999); (b) GESS (1999) (Courtesy of J. P. Bardet, University of Southern California); and (c) undamaged liquefied nitrogen tank (on right) and two liquefied oxygen tanks damaged during 1999 Kocaeli, Turkey earthquake

Fig. 15. (a) Undamaged silos; (b) silos damaged at SEKA paper mill during 1999 Kocaeli, Turkey earthquake (Sezen et al. 2000)

During the 1999 Kocaeli earthquake, two of the three aboveground tanks collapsed as a result of failure of reinforced concrete columns supporting the tanks [Fig. 14(c)]. The collapsed tanks contained liquefied oxygen and were 85% full, and the undamaged liquefied nitrogen tank was 25% full at the time of the earthquake. It is estimated that approximately 1,200 metric tons of cryogenic liquefied oxygen were released as a result of collapse of the two oxygen storage tanks. The liquefied nitrogen tank next to the collapsed tanks was virtually undamaged. Based on the detailed dynamic analyses of the tanks, Sezen et al. (2008) concluded that the sloshing of the stored fluid did not affect the tank response significantly, and the failure was mainly due to insufficient strength and deformation capacity of the columns supporting the oxygen tanks. They also concluded that if an elevated tank is desired in a seismic region, the strength and deformation capacity of the support columns should be increased considerably, or an alternative support structure should be used.

Three reinforced concrete silos at the state-owned paper mill, SEKA, collapsed during the 1999 Kocaeli earthquake. The paper mill was located approximately 20 km from the epicenter of the earthquake. Fig. 15 shows a photographs of two undamaged silos and a collapsed silo. The diameter of the silos was approximately 6 m. The collapsed silos were supported on six small square nonductile columns with minimal longitudinal reinforcement. The undamaged silos of Fig. 16 were supported on larger square columns than those of the collapsed silos.

Fig. 16. Collapse of concrete factory silo during 1999 Chi-Chi, Taiwan earthquake (GEER 1999 (Courtesy of J. P. Bardet, University of Southern California)



(a) (b)

Fig. 17. (a) General view; (b) severe concrete crushing and buckling of longitudinal bars of Corso Silo during 2003 Zemmouri, Algeria earthquake (Bechtoula and Ousalem 2005)

September 21, 1999 Chi-Chi, Taiwan Earthquake

An earthquake of occurred 7.6 magnitude in Taiwan at 1:47 a.m. on September 21, 1999. A concrete factory silo fell to the ground during the earthquake (Fig. 16). The upper portions of the collapsed silo suffered virtually no damage, suggesting that the integrity of the conical bottom segment and the anchorage to the foundation should be carefully considered during the seismic design of silos. Other silos that collapsed caused by the same earthquake were also reported. A report by EQE indicated that a food processing plant had several grain silos, which were filled with food products by the plant operators because of an impending typhoon predicted before the earthquake. When the earthquake hit, all of the full silos collapsed (EQE 1999).

May 21, 2003 Zemmouri, Algeria Earthquake

An earthquake with a magnitude of 6.8 and a focal depth of 10 km occurred in the boundary region between the Eurasian plate and the African plate on May 21, 2003. At least 2,266 people were killed, and 10,261 injured (USGS 2003). The earthquake caused severe damage to some storage facilities and equipment. The spectacular damage to the Corso silos was mostly concentrated in the walls near the bottom of the silos (Fig. 17). The silo complex was constructed during the 1970s near the city of Boumerdes. Five batteries compose the complex, which is founded on piles that are 24 m in length. Battery number five was the most damaged. At the time of the earthquake, the battery was nearly full with grain, whereas other batteries were either approximately half filled or almost empty. Severe concrete crushing, lack of sufficient reinforcement, steel bar fractures and buckling, and partial sliding of the external concrete shell were observed (Bechtoula and Ousalem 2005).

Conclusions

The main factors that cause damage in silos are reviewed and discussed. Explosion and bursting of the contained material, load variations during filling and discharging, nonuniform or large foundation pressure and soil conditions, corrosion in metal silos, internal structural collapse, deterioration of concrete silo walls, thermal ratcheting, and earthquakes are identified as the major factors contributing to silo failures. This paper presents a review of representative silo failures reported in the literature, which typically includes only a brief description of the damage or collapse. This research is unique because, unfortunately, very little or no technical information is available on silo failures and the contributing factors.

Explosion and bursting can be prevented by monitoring the internal pressure and gases produced by the stored bulk material. Similarly, if the effects of potential asymmetric flow patterns caused by ratholes, preferential flow channels, or asymmetric loading patterns created by the bulk material during filling or discharging are considered during the design process, the dent, buckling, and even collapse of the silos can be prevented. The base of the silo structure can be subjected to larger base pressure than that of the other traditional structures such as buildings. Nonuniform base pressure resulting from lateral loads, for instance earthquake loads or potential asymmetrical material loads during filling or discharging, should be considered in design. The wind loads can generally be effective for empty and light silos, while the horizontal seismic loads can be more critical for heavier and taller silo structures. Insufficient poorly detailed reinforcement in concrete support columns or concrete silo walls can exacerbate the damage and lead to failure. Corrosion of metal silos, deterioration of concrete silos due to silage acids, internal structural collapse, and thermal ratcheting are the other factors that can cause damage and failure.

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