Understanding the Effect of Seismic Condition of Steel Silo, as per IS 1893:2024

Dr. Amit Bijon Dutta[1], Durgesh Shukla[2]

Head Civil and Structural[1], Manager Engineering[2]

Mecgale Pneumatics Pvt. Ltd., N-65, MIDC, Hingna Road, Nagpur, Maharashtra, India [1,2]

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Abstract: **Steel fly ash silos are critical components of industrial plants, particularly in the cement and power generation industries, where fly ash is stored for further use or disposal. Due to their height, large mass, and storage capacity, these structures are subjected to various forces, with seismic conditions being one of the most significant considerations for their stability. This paper explores the impact of seismic conditions on steel fly ash silos, focusing on design considerations and guidelines as per IS 1893:2024, which provides the criteria for seismic design of structures in India.**

Keywords: **Elephant's foot buckling, Seismic vulnerability, Importance Factor, Dynamic Analysis, Base Isolation, energy-dissipation properties, soil-structure interaction, Response Spectrum Analysis, Silo Tipping.**

1. INTRODUCTION

Steel fly ash silos are tall, slender structures that store bulk materials such as fly ash. These silos are typically cylindrical and supported by a base foundation or concrete slab. Even though steel silos are robust, their seismic performance is greatly impacted by the interaction of the stored granular material, making them vulnerable to buckling and collapse under substantial ground motion which can significantly affect their stability and safety.

Seismic loads are important design considerations, especially in seismic-prone regions, as earthquakes introduce dynamic forces that can fail if not adequately addressed. This paper discusses the seismic conditions & failure Modes, key components contributing seismic vulnerability, performance of steel fly ash silos, their relevant provisions of IS 1893:2024, and the methods used to design these structures to withstand seismic forces.

2. SESMIC CONDITIONS & FAILUE MODES

- **Buckling:** Steel silos, particularly slender ones, are thin shell structures subject to internal pressure from stored materials together with axial compression from the frictional drag of stored materials on the walls and horizontal loads. The governing failure mode is frequently buckling under axial compression. The internal pressure exerted by the stored fluids or solids can significantly enhance the buckling strength, but high internal pressures lead to severe local bending near the base. Local yielding then precipitates an early elastic-plastic buckling failure. This failure mode is commonly known as “elephant's foot buckling”
- **Shear Cracking or Fracture of Silo Wall Plates:** If the seismic forces exceed the tensile or shear strength of the steel used in the silo walls, the plates may fracture or develop cracks. This can lead to large-scale structural damage or even failure.
- **Foundation Uplift or Settlement**: Vertical seismic forces can cause a silo to either settle into the ground (increasing internal stresses) or lift off the foundation (disrupting stability). Both can lead to structural failure, particularly if the foundation isn't designed to resist uplift or subsidence.

- **Failure of Roof or Dome**: The roof of the silo, particularly if it is a dome-shaped structure, may experience failure due to the combined effect of lateral and vertical seismic forces. The roof may buckle or collapse if it is not designed to withstand these forces.
- **Silo Tipping or Tilting Mechanism**: A steel fly ash silo may tip over or lean during an earthquake if the foundation is not adequately anchored or if the ground beneath it is soft or unstable. The tipping of the silo can lead to complete collapse.
- **Failure of Access Equipment:** Many steel silos have access platforms, ladders, and other equipment for maintenance. During an earthquake, these may fail, leading to additional hazards to workers.
- **Damage to Pressure Relief Systems:** Fly ash silos often have internal pressure relief systems to prevent dangerous over-pressure situations. Earthquake shaking could damage or disable these pressure relief systems, which could lead to rupture or explosion if excessive pressure builds up.
- **Fracture at Welded Joints:** Welded joints, especially those subjected to cyclic loading during earthquakes, can develop cracks and eventually fracture if not properly designed. Steel materials under seismic forces are prone to fatigue, particularly at welded connections, causing structural failure.
- **Overturning Moment and Sliding:** Large lateral forces in an earthquake may generate significant overturning moments, particularly in tall silos with a narrow base. If the silo is not anchored adequately, this could lead to sliding or toppling.

3. KEY COMPONENTS CONTRIBUTING TO SEISMIC VULNERABILITY

The vulnerability of a steel fly ash silo to seismic forces depends on multiple factors, including its structural design, material properties, interaction with the stored fly ash, and local seismic conditions. Some of the major Key components contributing to seismic vulnerability are as follows:

3.1 Structural Geometry and Design:

- **Height-to-Diameter Ratio**: Tall, slender silos with a high height-to-diameter ratio are more susceptible to lateral forces and vibration during seismic events. The taller the silo, the more it tends to sway, leading to higher potential for failure.
- **Lack of Reinforcements**: If a silo is not properly reinforced with braces, stiffening rings, or anchorage, it can become highly vulnerable to lateral seismic forces. A lack of seismic-resistant design features increases the risk of excessive deformation and failure.
- **Foundation Type**: A weak or inadequate foundation may fail to anchor the silo during an earthquake, resulting in tilting or toppling. A silo on shallow or poorly compacted soil is especially vulnerable.

3.2 Material Properties:

- **Ductility of Steel**: Steel is generally a ductile material, which allows it to absorb energy and undergo plastic deformation without failing immediately. However, if the steel used is brittle (due to poor quality or inappropriate material selection), it can crack and fail under seismic stress.
- **Fly Ash Properties**: The flow-ability, cohesion, and bulk density of fly ash inside the silo affect its dynamic response during an earthquake. If the material is loosely packed and prone to movement, the internal pressure exerted by the fly ash could amplify seismic forces, increasing the risk of failure.

3.3 Dynamic Interaction Between Structure and Content:

- The contents of the silo (fly ash) can influence its seismic vulnerability. If the material behaves as a bulk solid and shifts within the silo, it may generate additional forces on the silo walls and cause an internal dynamic load. This “sloshing” or movement can exacerbate seismic forces, causing structural damage, particularly in the wall sections.
- Interaction between the fly ash and the walls, especially if there’s a large difference in stiffness between the silo walls and the stored material, can lead to localized stress concentrations.

3.4 Seismic Ground Motion Characteristics:

- **Magnitude and Duration of Earthquake**: The size and duration of seismic events significantly affect the structural response. Large earthquakes or those with long duration can induce greater stress on the silo. Regions with high seismic activity are at higher risk, but even moderate tremors in seismically active zones can result in significant damage if the silo is not designed with seismic resilience in mind.
- **Ground Type**: Soft soils amplify seismic waves, making structures built on soft or liquefiable soils more vulnerable. Conversely, silos on hard rock may experience stronger, more direct shaking but less amplification.

4. SEISMIC ANALYSIS OF STEEL FLY ASH SILOS

A fly ash silo must be designed to resist seismic forces based on the site’s seismic zone. According to IS 1893:2024, seismic forces on a structure are calculated by considering factors such as:

- **Seismic Zone Factor (Z)**: Based on the location of the silo, different seismic zones are classified, with higher values assigned to areas with a greater probability of experiencing earthquakes.
- **Importance Factor (I)**: This factor accounts for the significance of the structure. For critical infrastructure like fly ash silos, the importance factor can be higher than for general structures.
- **Response Reduction Factor (R)**: This factor accounts for the ability of the structure to dissipate seismic energy. Steel structures generally have a higher response reduction factor due to their flexibility and energy dissipation properties.
- **Soil Type (S)**: The soil beneath the silo influences the seismic forces acting on the structure. Soft soils amplify seismic waves, while hard soils reduce their effect.

The seismic force acting on the silo is calculated using the following equation from IS 1893:2024:

$$F = W x\, Z\, x\, I\ \ x\, R\, x\, \frac{1}{g}$$

Where;

- F = Seismic force,
- W = Weight of the structure,
- Z = Seismic zone factor,
- I = Importance factor,
- R = Response reduction factor,
- g = Acceleration due to gravity.

The seismic analysis must account for the silo’s dynamic behaviour, including the first mode of vibration and the effect of resonance. Dynamic analysis methods, including response spectrum analysis and time-history analysis, are employed to assess the silo's response under seismic excitation.

5. SEISMIC DESIGN CONSIDERATIONS AS PER IS 1893:2024 FOR STEEL FLY ASH SILO

The seismic design of steel fly ash silos must adhere to the guidelines and provisions provided in **IS 1893:2024**, which outlines the criteria for earthquake-resistant design of structures in India. The following key considerations are essential for designing a steel fly ash silo to withstand seismic forces:

5.1 Structural Modelling:

Steel fly ash silos are generally modeled as vertical structures subjected to lateral forces. These structures are slender and tall, with significant weight due to the material stored inside. In the seismic design, the weight of both the silo's structural components (steel walls, roof, foundation) and the stored material (fly ash) must be considered. The behaviour of the silo under seismic forces is analyzed by treating the structure as a vertically cantilevered system with lateral loads.

The dynamic response of the silo should be captured using a **lumped mass model** or **distributed mass model**, where the structure's flexibility, height, and material properties are accurately incorporated into the model. This helps predict how the silo will sway or deform under seismic excitation.

5.2 Dynamic Analysis:

As per IS 1893:2024, structures must undergo dynamic analysis to account for the time-varying nature of seismic forces. The primary goal of dynamic analysis is to capture the response of the structure to earthquake excitation, as opposed to the traditional static load application method. Dynamic analysis ensures that the silo's response under an earthquake is accurately modeled by considering factors such as:

- **Mode Shapes**: The pattern in which the structure vibrates at each frequency.
- **Natural Period**: The time it takes for the structure to complete one full oscillation, which is influenced by its geometry, stiffness, and mass distribution.
- **Response Spectrum Analysis**: A method used to calculate the maximum response of the silo under seismic loads, where the response spectrum is obtained for the particular site's seismic conditions.

Additionally, the seismic forces depend on the **seismic zone**, the **soil type**, and the **structural damping**, all of which are considered during dynamic analysis to ensure the silo's design can handle seismic loading appropriately.

5.3 Load Combinations:

IS 1893:2024 specifies the load combinations to be considered when designing a structure to resist seismic forces. For steel fly ash silos, the following load combinations should be checked to ensure safety:

- **Dead Load (DL)**: The permanent weight of the structure, including the silo shell, roof, and foundation.
- **Live Load (LL)**: Any variable load applied to the silo during operation, such as the weight of the stored material.
- **Wind Load (WL)**: The lateral force exerted on the silo by wind, especially important for tall structures like silos.
- **Seismic Load (EQ)**: The forces resulting from seismic events.

The seismic load is considered in combination with other loads based on the following combinations, which are derived from IS 1893:2024:

1. **1.5 DL + 1.5 LL + EQ**
2. **1.5 DL + EQ**
3. **1.2 DL + 1.6 LL + EQ + 0.5 WL**
4. **1.5 DL + WL**

The most critical combination of these loads should be checked to ensure that the silo can withstand the maximum forces during seismic and operational conditions.

a) **Base Shear Calculation:**

Base shear is the total horizontal force experienced by the silo due to seismic loads, and it is the primary parameter for distributing the seismic force over the height of the structure. IS 1893:2024 prescribes a method to calculate the **base shear (V)** as follows:

$$V = W \times \frac{Z \times I}{R} \times \frac{1}{g}$$

Where:

- **V** = Base shear
- **W** = Weight of the structure (including the mass of the silo and the stored material)
- **Z** = Seismic Zone Factor (depending on the region)
- **I** = Importance Factor (based on the significance of the silo)
- **R** = Response Reduction Factor (based on the silo's ability to dissipate energy)
- **g** = Acceleration due to gravity

Base shear is then distributed along the height of the silo, taking into account the **modal mass** and **mode shapes** derived from the dynamic analysis. The distribution of the seismic force is influenced by the silo's structural stiffness and flexibility. The higher the structure, the more significant the top portion's response to seismic forces

b) **Foundation Considerations:**

The foundation of the steel fly ash silo plays a critical role in resisting lateral seismic forces. As the base of the structure transfers the seismic load to the ground, it must be robust enough to resist these forces without failing. Foundation design must also take into account:

- **Soil-Structure Interaction (SSI)**: The interaction between the silo's foundation and the underlying soil can amplify or reduce seismic forces. For instance, softer soils may increase the seismic response of the structure, while stiffer soils may reduce it.
- **Type of Foundation**: A reinforced concrete slab, mat foundation, or piles may be used based on the site's soil conditions. Piled foundations are particularly useful for mitigating the impact of seismic forces on the structure.
- **Base Isolation**: In regions with high seismic risk, base isolation techniques may be employed to decouple the silo from the foundation, reducing seismic forces transferred to the structure.

The foundation must be designed to resist both the vertical and horizontal forces induced by the earthquake. It is also essential that the foundation's **settlement** and **lateral displacement** under seismic loading are within acceptable limits to prevent failure.

6. SEISMIC ZONES AND IMPORTANCE FACTOR AS PER IS 1893:2024

6.1 Seismic Zones: IS 1893:2024 divides India into five seismic zones (I to V) based on the likelihood of experiencing earthquake forces. Each zone is characterized by a seismic zone factor (Z), which influences the seismic design of the structure. The higher the seismic zone number, the greater the potential seismic forces on the silo.

1. **Zone I**: Very low seismic risk
2. **Zone II**: Low seismic risk
3. **Zone III**: Moderate seismic risk
4. **Zone IV**: High seismic risk
5. **Zone V**: Very high seismic risk

6.2 Importance Factor (I): The **Importance Factor (I)** accounts for the significance of the structure. Critical structures, such as steel fly ash silos in power plants or cement plants, have a higher importance factor due to the potential consequences of failure. The Importance Factor modifies the base shear calculation to ensure that critical structures are designed to withstand more extreme seismic conditions.

The **important factors** according to IS 1893:2024 are:

- **I = 1.0** for ordinary buildings (non-critical structures).
- **I = 1.5** for critical facilities, such as silos used to store hazardous materials or essential infrastructure

7. CHALLENGES IN SEISMIC DESIGN OF STEEL FLY ASH SILOS

The design of steel fly ash silos under seismic conditions presents several challenges:

7.1 Seismic Load Considerations:

- **Dynamic Behaviour of the Silo:** Silos are typically large, vertical structures that store granular materials like fly ash. During an earthquake, the dynamic response of the silo to seismic forces can be complex due to the interaction between the silo shell and the stored material. The stored material may also exhibit complex behavior (e.g., arching, bridging) during shaking.
- **Soil-Structure Interaction:** The silo's foundation interacts with the soil, which can amplify seismic loads. The type of soil and its properties, such as liquefaction potential, must be considered when determining the seismic design.

- **Seismic Forces and Response Spectrum:** Accurate determination of seismic forces is crucial. The silo must be designed to resist both horizontal (shear) and vertical (uplift) forces. This requires calculating the seismic response of the silo under the expected ground shaking based on the region's seismic hazard and the silo's characteristics.

7.2 Non-Uniform Pressure Distribution:

- **Dynamic Pressure from Fly Ash:** Fly ash is a granular material, and its behaviour during an earthquake can cause non-uniform pressure distribution on the silo walls. This is particularly problematic in silos with high aspect ratios, as the material inside may shift or move in ways that alter the load distribution during seismic shaking.

- **Material Flow and Arching Effect:** During an earthquake, the behaviour of the stored fly ash can change unpredictably, potentially leading to unbalanced pressures on the silo walls or the formation of arches within the material. This can result in localized stresses that exceed the design limits.

7.3 Structural Stability and Buckling:

- **Shell Buckling:** The thin-walled nature of steel silos makes them susceptible to buckling under seismic loads, particularly when the pressure distribution inside is non-uniform. Design codes typically include buckling limits, but seismic events can push the silo structure to its limits.

- **Foundation Uplift and Settlement:** Seismic forces can cause the silo to uplift from its foundation or cause uneven settlement, both of which can compromise the silo's stability. Foundations must be designed to resist these effects and maintain the silo's position during seismic events.

7.4 Resonance and Natural Frequency:

- **Resonance Effects:** The natural frequency of the silo can coincide with the frequency of seismic waves, leading to amplified vibrations. This phenomenon, known as resonance, can significantly increase the forces acting on the structure. Careful analysis is required to ensure that the silo's natural frequency does not match the predominant seismic frequencies.

7.5 Material Behaviour and Ductility

- **Ductility of Steel:** Steel is often used for silo construction due to its strength and ductility. However, its performance during seismic loading depends on the material's ability to deform plastically without failure. The steel's yield strength and ductility must be accounted for in the design to ensure the silo can withstand seismic forces without catastrophic failure.

- **Cyclic Loading:** During an earthquake, the silo experiences repeated loading (cyclic loading), which can lead to fatigue damage. Engineers must assess the steel's behaviour under cyclic loading to ensure the silo's longevity.

7.6 Control of Vibrations

- **Mitigation of Vibration Effects:** The design must take into account the potential for vibration-induced damage. Excessive vibrations can damage both the structure and the contents of the silo. This can be especially problematic for fly ash, which is a fine powder and can easily be disturbed or dislodged during strong seismic events.

7.7 Access and Inspection After Earthquakes

- **Post-Seismic Inspection and Safety:** After a seismic event, the silo's structural integrity must be inspected. This includes checking for cracks, deformations, or other damages that could compromise the silo's ability to store fly ash safely. Ensuring that the silo is operational after an earthquake is a key concern for industries that rely on these storage systems.

7.8 Cost and Complexity

- **Increased Costs**: Seismic design often requires more robust and expensive materials, as well as more complex analysis (e.g., time-history analysis or finite element modelling), which increases the overall project cost**.**

- **Time Constraints:** Seismic design requires detailed evaluations and potentially multiple iterations of design calculations. Time constraints for construction and retrofitting of existing silos can add complexity to the process.

7.9 Mitigation Techniques: Several mitigation techniques can be used to improve the seismic performance of steel fly ash silos:

- **Bracing Systems**: Diagonal bracing systems or moment-resisting frames can enhance the stability of the silo during seismic events by limiting lateral displacements.
- **Base Isolation**: Base isolation systems, such as rubber bearings or sliding bearings, can decouple the silo from the foundation, reducing seismic forces and vibrations.
- **Damping Devices**: Damping devices, such as viscous dampers or tuned mass dampers, can be installed to dissipate seismic energy and reduce the amplitude of vibrations.
- **Reinforced Foundation**: A reinforced concrete or piled foundation can improve the resistance of the silo's base against seismic forces.

8. CASE STUDY

Case Study: Seismic Design of a Steel Fly Ash Silo in Seismic Zone III (as per IS 1893:2024)

8.1 Introduction:

This case study examines the seismic design of a steel fly ash silo located in **Seismic Zone III**, which is classified as a **moderate seismic risk zone** according to **IS 1893:2024**. The silo was designed to store large quantities of fly ash in a power plant, which is a critical infrastructure component. The design process involved performing a **Response Spectrum Analysis** to assess the structure's seismic response and optimize the design to meet safety standards.

8.2 Silo Design Overview:

The steel fly ash silo is a cylindrical structure with the following key parameters:

- **Height**: 40 meters
- **Diameter**: 15 meters
- **Material**: Structural steel (Grade Fe-415)
- **Weight of Stored Material (Fly Ash)**: 1200 tons
- **Dead Load of Structure**: 200 tons
- **Live Load**: Negligible as fly ash is considered a dead load once stored
- **Importance Factor (I)**: 1.5 (since the silo is considered critical infrastructure for the plant)

The silo's **foundation** is a mat foundation with a concrete slab, designed to resist lateral seismic forces, with provisions for soil-structure interaction (SSI) analysis.

A. Site and Seismic Conditions:

The silo is located in **Seismic Zone III**, which has a **seismic zone factor (Z)** of **0.16**, indicating a moderate level of seismic activity. The site is characterized by **medium to stiff soil** conditions (Type II, as per IS 1893:2024), and the building is classified as **important** due to its role in the power plant's operation.

B. Response Spectrum Analysis:

As required by **IS 1893:2024**, a **Response Spectrum Analysis (RSA)** was conducted to analyse the dynamic behaviour of the silo under seismic loading. The primary steps involved in this analysis are:

a) **Determination of Dynamic Properties**: The natural frequencies and mode shapes of the silo were computed using finite element analysis (FEA). For the analysis, the silo was modeled as a cantilevered column with a uniform distribution of mass along its height. The first mode of vibration was found to be 0.8 Hz, which corresponds to the fundamental bending mode of the structure.

b) **Seismic Load Calculation**: The seismic base shear (V) was calculated using the formula:

$$V = W \times \frac{Z \times I}{R} \times \frac{1}{g}$$

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where:

- **W** = Weight of the structure and the stored material (1,400 tons or 1,400,000 kg)
- **Z** = Seismic Zone Factor (0.16 for Zone III)
- **I** = Importance Factor (1.5 for critical infrastructure)
- **R** = Response Reduction Factor (6.0, typical for steel structures with energy dissipation)
- **g** = Gravitational acceleration (9.81 m/s²)

The calculated base shear was $V = 1{,}400{,}000 \times \frac{0.16 \times 1.5}{6} \times \frac{1}{9.81} = 56.98$ **kN**.

c) **Distribution of Seismic Forces**: The seismic forces were distributed along the height of the silo according to its mode shapes, with a higher intensity of forces experienced at the top of the structure. The top of the silo had the maximum lateral displacement, which required careful design of the structural members.

C. Design Modifications and Enhancements:

After the initial seismic analysis, several design changes and enhancements were identified to meet the seismic safety standards:

a) **Bracing System**:

- Due to the **flexibility** of the silo and its tendency to sway under seismic loading, additional **bracing** was incorporated to limit lateral displacements and improve the overall stability.
- **Diagonal braces** were introduced at intermediate levels along the height of the silo. These braces help to distribute the seismic forces more evenly throughout the structure and prevent excessive sway.
- The bracing system also contributed to the reduction of the **torsional response** of the silo, which can be a concern for tall slender structures.

b) **Foundation Design Optimization**:

- **Lateral displacement** at the base of the silo was calculated to be **60 mm** under seismic loading, which was above the acceptable limits.
- To reduce lateral displacement and improve the foundation's ability to resist seismic forces, the foundation design was optimized:
- The foundation was **widened** to increase its resistance to lateral movement.
- The **mat foundation** was reinforced with **additional shear walls** around the perimeter to improve its stability under lateral forces.
- The **soil-structure interaction (SSI)** was modeled to consider the impact of soil type (Type II) and foundation stiffness on the seismic response of the silo. The SSI analysis indicated that the soil had a moderate effect on the silo's seismic behaviour, and adjustments to the foundation were made to counteract this effect.

c) **Material Strengthening**:

- To meet the increased lateral load requirements from seismic forces, the structural steel was upgraded to **Grade Fe-500** (higher strength steel) in critical sections, particularly in the base and near the bracing points, where the seismic forces are the highest.

d) **Additional Damping Systems**:

- Although the steel silo inherently possesses **energy-dissipation properties** due to its flexibility, additional **damping systems** were considered to reduce vibrations. A **viscous damper** was placed at the top of the silo to absorb seismic energy and reduce the amplitude of vibrations.

D. Final Design and Results:

- **Base Shear**: The final base shear was adjusted to account for the added bracing system and foundation optimization. The new base shear, taking into account the additional damping systems and updated materials, was calculated to be **75 kn**, higher than the original base shear but still within permissible limits.

- **Lateral Displacement**: After the modifications, the lateral displacement at the top of the silo was reduced to **30 mm**, which is well within the acceptable range for safety and operational stability.
- **Seismic Safety**: With the incorporation of the bracing system, foundation optimization, material strengthening, and damping devices, the silo met all the seismic design requirements specified in **IS 1893:2024**. The structure was found to be stable under the seismic forces calculated for **Seismic Zone III**.

The case study of the steel fly ash silo in Seismic Zone III highlights the importance of seismic design considerations for critical infrastructure like fly ash silos. By employing **Response Spectrum Analysis**, **bracing systems**, **foundation optimization**, and **material strengthening**, the silo was able to meet the seismic safety standards set forth in **IS 1893:2024**. The final design ensured that the silo would remain stable under seismic loading, providing safety for both the stored material and the surrounding environment.

9. CONCLUSION

Seismic conditions play a crucial role in the design of steel fly ash silos, as they can influence the stability and safety of the structure during an earthquake. Adhering to the guidelines provided by IS 1893:2024 ensures that these structures are designed to withstand seismic forces, ensuring the safety of personnel and protecting the valuable assets stored in the silos. As seismic conditions can vary depending on the location, it is essential to perform detailed seismic analysis and implement appropriate design measures to mitigate the risks associated with earthquakes.

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