

Seismic Analysis and Design Considerations of RCC Silo Structures in Indian Seismic Zones: A Review

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Abstract—Reinforced cement concrete (RCC) silos are special industrial storage structures used for storing granular and powder materials such as cement, fly ash, coal, clinker and food grains. Unlike conventional buildings, silo walls are subjected to self-weight, stored material pressure, wall friction, wind loading, seismic loading, operational filling and discharge effects, and possible dynamic overpressure generated by stored material during earthquake excitation. This review paper presents a consolidated study of seismic analysis and design considerations for RCC silo structures in Indian seismic zones. The review focuses on pressure estimation using Janssen theory, finite element modelling using STAAD.Pro, seismic force application based on Indian codal provisions, hopper geometry effects, soil condition influence, natural frequency response and stress concentration zones. Literature from analytical, numerical and code-based studies shows that stored material–structure interaction, height-to-diameter ratio, hopper arrangement, soil flexibility and lateral load-resisting systems strongly influence the seismic performance of silo structures. The review also summarizes representative findings from the uploaded dissertation report, where double hopper configuration reduced maximum absolute stress from 4.80 MPa to 4.41 MPa and reduced X-direction moment from 11.6 to 6.81, while soft soil increased absolute stress to 7.38 MPa. The study concludes that circular hopper geometry, proper seismic detailing, accurate stored material pressure calculation and finite element-based assessment are essential for safe and economical RCC silo design in earthquake-prone regions.

Index Terms—RCC silo, seismic analysis, Janssen theory, STAAD.Pro, stored material pressure, hopper configuration, finite element analysis, Indian seismic zone.

I. INTRODUCTION

Silos are widely used in cement plants, thermal power stations, mining industries, agricultural grain storage systems and material-handling facilities. They are generally designed to store large quantities of granular or powder materials in a vertical container. The structural action of a silo is significantly different from that of an ordinary framed building because the stored material continuously interacts with the container wall through lateral pressure and wall friction. During an earthquake, the stored material behaves as an internal dynamic mass and may develop additional pressure on the wall, hopper and supporting system.

RCC silos are commonly preferred where durability, fire resistance, stiffness and long service life are required. However, their high mass and slender geometry make them vulnerable to lateral forces. The earthquake response of a silo depends on the self-weight of the structure, weight of stored material, seismic zone factor, soil type, support condition, structural stiffness, wall thickness, filling level, hopper arrangement and the dynamic characteristics of the stored bulk solid. Therefore, static pressure alone is not adequate for a reliable seismic design.

The uploaded dissertation report entitled “Analysis and Design of RCC Silo Structure by Using Considering Indian Seismic Zone” investigates this problem using STAAD.Pro finite element modelling. It highlights that ignoring or underestimating dynamic pressure and soil influence may lead to excessive stress, displacement, bending moment and possible failure. This paper converts the study into an IEEE-style review paper by synthesizing the available literature, identifying the research gap and presenting key design implications for RCC silo structures subjected to Indian seismic conditions.

II. STRUCTURAL BEHAVIOUR AND LOADING OF RCC SILOS

A. Stored Material Pressure

The most important load in silo design is the pressure exerted by the stored material. This pressure is governed by unit weight, internal friction angle, wall friction coefficient, filling height, silo radius and flow pattern. In contrast with liquid pressure, the lateral pressure of granular material does not increase linearly with depth because part of the vertical load is transferred to the wall through friction. Janssen theory is widely used to estimate this pressure because it accounts for wall friction and limiting pressure conditions.

In RCC silo analysis, horizontal pressure produces hoop tension, wall bending and local stress concentration. Vertical wall friction produces axial compression in the silo wall. The hopper region is especially critical because load transfer changes from vertical wall action to inclined discharge action, causing bending and shear concentration near the wall-hopper junction.

B. Seismic and Dynamic Effects

During earthquake excitation, the silo wall, supporting system and stored material vibrate together. The stored material contributes to the seismic mass and also generates additional dynamic lateral pressure on the wall. Conventional practice sometimes treats the stored material as a lumped mass, which is useful for approximate base shear calculation but may not fully represent wall pressure distribution. A realistic design must therefore combine codal seismic force calculation with finite element evaluation of stress and moment distribution.

The major seismic response parameters of RCC silos are base shear, overturning moment, lateral displacement, natural frequency, time period, wall stress, membrane force, shear stress and bending moment. Damage is commonly expected near the base, wall-hopper junction, support connection and regions of abrupt geometry change.

C. Soil Condition and Support Flexibility

The supporting soil condition influences seismic amplification and foundation flexibility. Hard soil generally gives lower deformation and stress demand, whereas soft soil can increase displacement, stress and moment response. Therefore, silo design in higher seismic zones must consider soil category and, where necessary, soil-structure interaction. The report results confirm this trend because soft soil produced the most critical absolute stress and moment values.

III. REVIEW OF PREVIOUS STUDIES

A review of published studies shows that the seismic behaviour of silo structures has been studied using analytical models, equivalent static method, response spectrum analysis, time-history analysis, finite element models, shell models and granular material interaction models. Table I summarizes the important studies and their contribution to RCC or steel silo seismic assessment.

TABLE I

SUMMARY OF SELECTED LITERATURE ON SEISMIC AND DYNAMIC BEHAVIOUR OF SILOS

Ref.	Author/Year	Method / Model	Main Focus	Key Contribution
[1]	Vickery and Clark, 1972	Experimental/dynamic study	Wind-induced response of tall structures	Highlighted the importance of dynamic response in slender storage-type structures.
[2], [3]	Veletsos and Younan, 1998	Analytical model	Dynamics of solid-containing tanks	Provided an important basis for stored solid-container interaction.
[6]	Chowdhury and Tilak, 2010	Modified Janssen approach	Dynamic pressure on circular silos	Showed that earthquake-induced pressure on silo walls should not be ignored.
[8]	Nateghi and	ABAQUS FE model	Granular material-structure	Found that height-to-diameter ratio and content interaction control

	Yakhchalian, 2012		interaction	seismic pressure.
[9]	Kharjule and Jagtap, 2015	Response spectrum and time history	RCC and steel silos	Observed lower displacement when shear walls or steel plates are provided.
[10]	Bidari and Vishwanath, 2014	SAP2000 analysis	Braced and unbraced support systems	Concluded that bracing improves stiffness and reduces lateral displacement.
[11]	Dhundasi and Ishwaragol, 2016	SAP2000 response spectrum	Lateral load-resisting systems	Reported displacement reduction using shear plates and bracing.
[12]	Hirde and Mohabansi, 2022	Seismic evaluation	Steel silos with different aspect ratios	Showed that slenderness increases displacement and overturning effect.
[13]	Mansour et al., 2022	Comprehensive review	Flat-bottom silos with granular material	Identified effective mass, period and dynamic overpressure as unresolved design issues.
[14]	Mansour and Silvestri, 2025	Code formula review	EN1998-4 pressure formula	Reported possible overestimation of additional pressure in circular silos.
[15]	Awadhbihari and Sawant, 2025	STAAD.Pro time-history analysis	RC silo in Indian seismic zones	Reported increasing displacement and base shear from Zone II to Zone V.
[16]	IS 4995 and IS 1893	Indian codal provisions	RCC bin loads and earthquake design	Provide general requirements for stored material pressure and seismic force calculation.

IV. RESEARCH GAP IDENTIFIED FROM THE REVIEW

The reviewed studies show that silo design is still affected by several unresolved issues. Many design approaches simplify the stored material as a lumped mass and neglect the actual distribution of dynamic pressure on the wall. This simplification may be unconservative for slender silos and may also miss local stress concentration at wall-hopper junctions.

Another important gap is the limited integration of hopper geometry, soil condition, Indian seismic zone effects and finite element stress interpretation within a single framework. Several studies focus either on steel silos, elevated silos or general granular interaction, whereas fewer studies focus specifically on RCC silo structures analysed using practical design software such as STAAD.Pro under Indian seismic provisions.

Experimental validation is also limited because large-scale silo testing is expensive. As a result, most studies rely on numerical modelling and code-based calculations. Future research must therefore improve model validation, include soil-structure interaction, compare multiple stored materials and incorporate nonlinear time-history analysis using recorded earthquake motions.

V. METHODOLOGY FRAMEWORK FOR RCC SILO REVIEW

The methodology followed in the uploaded report is analytical and finite element based. The silo geometry is selected first, followed by material properties, stored material properties, support conditions and loading cases. The silo wall is discretized using finite plate elements in STAAD.Pro so that local stress and moment distribution can be evaluated more accurately than by a simplified hand calculation.

The stored material pressure is calculated using Janssen theory. Seismic loading is then applied according to Indian seismic design provisions. Dead load, stored material pressure and seismic load combinations are considered to evaluate wall stresses, shear stresses, bending moments, natural frequency and time period. The model is validated by comparing analytical natural frequency and time period with STAAD.Pro output.

This framework is suitable for review and preliminary design because it combines codal calculations with finite element-based stress visualization. However, the accuracy of the method depends on assumed material properties, boundary conditions, element discretization, soil condition and representation of stored material behaviour.

TABLE II**REVIEW-BASED MODELLING AND ASSESSMENT PARAMETERS**

Stage	Parameter	Design/Review Consideration
Geometry selection	Shape, height, diameter, hopper type	Circular and symmetrical geometry generally reduces stress concentration.
Material definition	Concrete, steel reinforcement, stored material	Bulk density, internal friction and wall friction control pressure distribution.
Pressure calculation	Janssen theory	Suitable for static stored material pressure because wall friction limits lateral pressure.
Seismic loading	Indian seismic zone, soil type, importance factor	Controls base shear, displacement and dynamic pressure demand.
Finite element modelling	Plate element wall discretization	Allows identification of local stress and moment concentration zones.
Validation	Natural frequency and time period	Analytical and software results should be checked before final interpretation.
Performance assessment	Stress, shear, moment, frequency, displacement	Critical regions should be detailed for ductility and crack control.

VI. COMPARATIVE DISCUSSION OF REPORTED RESULTS

A. Single Hopper and Double Hopper Response

The comparison between single hopper and double hopper silos shows that hopper arrangement has a strong influence on stress and moment distribution. The single hopper model develops a maximum absolute stress of 4.80 MPa, whereas the double hopper model develops 4.41 MPa. This indicates that the double hopper configuration can reduce the peak absolute stress by distributing load through two discharge paths.

In the X-direction, the maximum shear stress reduces from 1.39 MPa in the single hopper silo to 1.26 MPa in the double hopper silo. The X-direction bending moment also reduces from 11.6 to 6.81. However, the double hopper silo shows higher Y-direction and XY-direction moments. Hence, the double hopper arrangement is beneficial in some response components but requires careful reinforcement detailing in both principal directions.

B. Soil Condition Effect

The soil condition study confirms that soft soil is the most critical condition for seismic silo response. Maximum absolute stress increases from 4.80 MPa in hard soil to 6.33 MPa in medium soil and 7.38 MPa in soft soil. Similarly, bending moments increase significantly with soil flexibility. This result agrees with general seismic design behaviour, where soft soil can amplify structural response and increase deformation demand.

For practical design, foundation stiffness and site soil classification should not be treated as secondary considerations. RCC silos located on soft soil require careful foundation design, lateral stiffness evaluation and seismic detailing.

C. Rectangular and Circular Hopper Comparison

The comparison between rectangular and circular hopper geometry indicates that circular hopper configuration performs better by reducing stress concentration and producing a more uniform load transfer mechanism. The reported results show that circular hopper geometry reduces shear and moment demand compared with rectangular hopper geometry. This confirms the structural advantage of smooth and symmetric forms in silo design.

D. Dynamic Properties

The single hopper silo shows higher natural frequencies than the double hopper silo in the first modes, indicating a relatively stiffer dynamic response. The double hopper model shows lower frequencies and higher time periods, which suggests greater flexibility. In seismic design, this difference is important because natural frequency and time period influence spectral acceleration, displacement demand and force distribution.

VII. DESIGN IMPLICATIONS

- Stored material pressure should be calculated using an appropriate theory such as Janssen theory rather than assuming hydrostatic pressure distribution.
- Dynamic pressure generated by stored material during earthquake excitation should be considered, especially for tall and heavily loaded silos.
- Circular and symmetrical silo or hopper geometries are generally preferable because they reduce local stress concentration.
- Double hopper systems may reduce some stress and moment components, but reinforcement should be checked in both X and Y directions because directional response may vary.
- Soft soil conditions can significantly increase stress and moment demand; therefore, site-specific soil classification and foundation stiffness should be included in seismic design.
- Finite element analysis using plate elements is useful for locating critical zones near the base, hopper connection and support region.
- Ductile detailing, crack control reinforcement and careful connection design are necessary in higher Indian seismic zones.

VIII. CONCLUSION

This review paper presents a consolidated IEEE-style discussion on the seismic analysis and design considerations of RCC silo structures under Indian seismic zone conditions. The review confirms that silos cannot be analysed as ordinary building structures because stored material pressure, wall friction, hopper geometry, dynamic overpressure and support condition strongly influence their response. The literature indicates that dynamic pressure, effective stored material mass, silo slenderness, granular material–wall interaction and soil flexibility remain major challenges in seismic silo design. The uploaded report supports these observations through STAAD.Pro-based finite element analysis of single and double hopper configurations. The numerical findings show that double hopper systems can reduce maximum absolute stress and X-direction bending moment, while soft soil produces the most critical stress and moment response. Circular hopper geometry is found to be more favourable for safe and economical design because it provides more uniform load transfer and lower stress concentration. Overall, RCC silo design in earthquake-prone regions should combine codal pressure calculations, seismic analysis, finite element modelling and careful detailing of critical zones. Future work should include nonlinear time-history analysis, soil-structure interaction, multiple filling levels, different stored materials and experimental or field validation of numerical models.

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