

Analysis and Design of RCC Silo Structure Considering Indian Seismic Zone

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Abstract

Silos are essential storage structures used in cement plants, thermal power stations, mines, grain storage units and other industrial facilities for storing bulk granular and powder materials. Their structural behaviour differs from ordinary building systems because the wall is subjected not only to self-weight and lateral environmental actions, but also to stored material pressure, wall friction, filling-discharge effects and seismic inertia of the stored mass. The present research investigates the finite element analysis and design behaviour of a silo structure under Indian seismic zone conditions using STAAD.Pro. Janssen theory is used for estimating lateral pressure on the silo wall, while the seismic action is considered through the response of the structural model under earthquake loading. The investigation compares single hopper and double hopper configurations, examines the influence of soil condition, validates the STAAD.Pro model using analytical natural frequency and time period values, and studies the variation of absolute stress, shear stress, bending moment and modal response. The results indicate that the double hopper arrangement reduces maximum absolute stress from 4.80 MPa to 4.41 MPa and reduces X-direction shear stress from 1.39 MPa to 1.26 MPa, but it increases Y-direction shear and Y-direction moment demand. Soft soil produces the most critical response, with absolute stress increasing to 7.38 MPa and M_x , M_y and M_{xy} moments increasing to 19.2, 22.4 and 12.6, respectively. The circular hopper comparison further indicates lower shear and moment response than the rectangular hopper.

Keywords: *RCC silo; STAAD.Pro; seismic analysis; Janssen theory; stored material pressure; hopper configuration; natural frequency; finite element analysis.*

1. Introduction

Silo, bin and bunker structures are widely used for the vertical storage of bulk solids such as cement, grain, coal, fly ash, crushed stone, ore and similar industrial materials. Shallow storage structures are commonly identified as bunkers or bins, while tall storage structures used for grains, cement and heavy granular materials are generally known as silos. These structures may rest directly on the ground or may be elevated on staging systems, and their plan geometry may be circular, square, rectangular or polygonal depending on the storage requirement and discharge arrangement.

The design of a silo is governed by the type and properties of stored material. Bulk density, angle of internal friction, coefficient of wall friction, filling height and flow pattern strongly influence the pressure acting on the wall. Unlike conventional buildings, silo walls are subjected to normal pressure and vertical frictional traction produced by the stored material. During earthquake excitation, the stored material also behaves as an additional mass and develops dynamic pressure on the wall. This makes silo analysis more complex than the analysis of ordinary RCC structures.

Silo failure can occur due to design error, construction defect, unsuitable use, maintenance problems or inadequate seismic assessment. Past earthquake damage to silo structures has shown that poor assumptions regarding material pressure and seismic interaction may result in cracking, buckling, local wall failure or partial collapse. Therefore, finite element modelling using software such as STAAD.Pro is useful for estimating stresses, bending moments, displacement and modal properties in a systematic manner.

2. Literature Review

Vickery and Clark (1972) investigated the lift or cross-wind response of tapered stacks through experimental study and explained the importance of vortex shedding in the dynamic behaviour of tall slender structures. Their abstract-level contribution shows that the maximum response in the fundamental mode occurs when the vortex shedding frequency at nearly one-third of the stack height becomes equal to the natural frequency of the structure. This finding was important because earlier studies considered vortex shedding near the top of the structure as more critical, whereas their study

proved that the response mechanism can be different depending on height and flow condition. Marzouk and Sayed (1973) developed the linear theory of orthotropic cylindrical shells, particularly for corrugated steel shell structures, and explained how membrane rigidity and bending rigidity in the circumferential and longitudinal directions affect shell behaviour. Their work is relevant to silo analysis because silos behave like cylindrical shell structures, and accurate shell theory is required to study stress distribution, bending behaviour and boundary effects. Briassoulis (1992) proposed an integrated physical model for cylindrical shells by combining beam action, plate bending action, meridional membrane action and equivalent ring foundation action. The study showed that cylindrical shell behaviour depends on load harmonics and shell characteristics, and the model can simulate thin-walled closed cylindrical shells under lower and higher harmonic loads. Silvestri, Trombetti and Gasparini (2008) studied flat-bottom grain silos under earthquake ground motion and proposed an innovative method for evaluating seismic actions on silo walls. Their study showed that the whole stored grain mass does not actively push against the silo wall during earthquake excitation. Instead, only a certain portion of the stored material interacts with the wall depending on the silo height-to-diameter ratio and material behaviour. This is very important for seismic silo design because considering the full stored material as active seismic mass may lead to unrealistic pressure estimation. Chowdhury and Tilak (2010) studied dynamic pressure on circular silos under seismic force and modified Janssen's theory to include the effect of horizontal and vertical seismic acceleration. Their abstract-level contribution is highly relevant to the present research because they observed that conventional silo design often considers the silo and stored material as a lumped mass only for supporting frame design, while the additional pressure generated on the silo wall due to vibration of stored material is generally ignored. Their study reported that dynamic pressure may increase by about 37–40% compared with ordinary Janssen static pressure, depending on staging configuration and support condition. Therefore, these five studies provide the basic theoretical foundation for understanding wind response, cylindrical shell behaviour, silo wall pressure, earthquake-induced dynamic pressure and the importance of stored material interaction in silo design.

Younan and Veletsos (1998) studied the dynamics of solid-containing tanks and provided an important analytical basis for understanding the interaction between stored solid material and circular containment structures. Their work considered the stored material as a uniform viscoelastic solid bonded to a non-deformable base subjected to horizontal motion. The study was divided into rigid tank and flexible tank behaviour, where Part A focused on rigid tanks and Part B discussed the effect of wall flexibility. This research is useful for silo analysis because it explains how stored material properties, tank-height-to-radius ratio and wall flexibility influence seismic response. Nateghi and Yakhchalian (2012) investigated the seismic behaviour of silos with different height-to-diameter ratios considering granular material–structure interaction using finite element modelling in ABAQUS. Their study modelled the silo wall with shell elements and the granular material with solid elements using a hypoplastic constitutive model. The research showed that silo slenderness has a major influence on seismic pressure distribution and wall stress, and it also emphasized that assuming constant acceleration over the height may be conservative for squat silos but unsafe for slender silos. Pieraccini and Vittuari (2017) studied the seismic behaviour of ground-supported circular silos containing grain-like material and reviewed analytical, numerical and experimental approaches for flat-bottom cylindrical grain silos. Their work emphasized that only part of the stored grain mass actively interacts with the silo wall during earthquake loading, and this effective mass depends on slenderness ratio, wall friction, acceleration level and grain-wall interaction. Khilare and Patil (2017) analysed steel silos subjected to specified ground motion using Janssen's theory and STAAD.Pro-based dynamic analysis. Their study considered pressure calculation, seismic action, base shear comparison and dynamic response under ground motion such as El-Centro earthquake data. They concluded that seismic loading significantly affects pressure distribution, natural frequency, time period, base shear and wall pressure, and therefore dynamic analysis is necessary for realistic silo behaviour. Mohod and Dhamge (2022) reviewed the design and analysis of reinforced concrete silos by considering different Indian seismic zones and different silo shapes such as circular, rectangular and square silos. Their study highlighted that circular silos generally develop lower stress and bending moment values compared with square and rectangular silos, while base shear and lateral displacement increase from lower to higher seismic zones. Overall, these studies show that seismic silo behaviour cannot be understood only through ordinary static pressure calculation. A realistic approach requires consideration of stored material pressure, dynamic pressure, wall flexibility, height-to-diameter ratio, support condition, seismic zone and finite element modelling. This literature strongly supports the present study because the current research uses STAAD.Pro-based finite element analysis to evaluate RCC silo behaviour under Indian seismic zone conditions while focusing on stress, time period, natural frequency and possible failure zones.

3. Research Gap

The research gap identified from the reviewed work is that many practical silo analyses still treat stored material as a lumped mass and do not fully capture the interaction between granular material, wall pressure, support conditions, seismic zone and hopper geometry. Limited integrated studies are available in which stress response, moment response, modal validation, soil influence and shape comparison are considered together. This paper therefore presents a finite element-based assessment of silo behaviour under Indian seismic zone conditions with direct comparison of single and double hopper arrangements and additional evaluation of soil and geometric effects.

4. Aim and Objectives

AIM

To demonstrate the finite element analysis on the effect of 5000tonnes loads on reinforced concrete silo at the mine under study

OBJECTIVE

1. The objective of the report is to give an estimation of the SFR Silos ability to withstand earthquake loads. There was no predefined load that the structure was required to withstand, so the aim have been to find the critical load instead – the load level for which the integrity of the structure is compromised.
2. The estimation of the capacity is nevertheless restricted by the assumptions and simplifications that were made in the modeling and analysis phases.
3. To determine the stress subjected to silo and compare to desired threshold
4. To determine the stress factor of the silo and points of failure of the silo

5. Materials and Methods

The study follows an analytical and finite element-based methodology. The silo geometry is defined first, followed by selection of material properties, stored material characteristics, support conditions and load cases. The silo wall is modelled using plate elements so that the variation of stress and moment across the wall and hopper region can be observed. The base is assumed to be fixed and the stored material is assumed to be uniformly distributed throughout the silo depth. Temperature effects, construction imperfections and detailed soil-structure interaction are not considered in the numerical model.

Stored material pressure is calculated using Janssen theory, which accounts for wall friction and horizontal pressure ratio. This method is appropriate for granular materials because the lateral pressure in a silo does not increase linearly like hydrostatic pressure. After pressure calculation, the loads are applied in STAAD.Pro together with self-weight and seismic loading. The model is then analysed to obtain absolute stress, membrane shear stresses S_x , S_y and S_{xy} , bending moments M_x , M_y and M_{xy} , natural frequency and time period.

Table 1. Problem statement and modelling parameters used in the analysis.

Parameter	Single hopper silo	Double hopper silo
Purpose of silo	Storage of cement	Storage of cement
Configuration	A single free standing rectangular shape	Double free standing rectangular shape
Height of silo	12 m	12 m
Length	3 m	1.5 m
Width	3 m	1.5 m
Thickness of silo	20 mm	20 mm
Storage product density	15.50 kN/m ³	15.50 kN/m ³
Angle of internal friction	25 degrees	25 degrees
Friction coefficient of tank wall	0.46	0.46
Seismic zone	III	III
Grade of steel	Fe500	Fe500

6. Validation of STAAD.Pro Model

The STAAD.Pro model was validated using the natural frequency and time period of the single hopper silo. The analytical model was idealized as a single-degree-of-freedom system, and its first three modal properties were compared with the software output. The comparison indicates that STAAD.Pro gives slightly higher natural frequency and lower time period values, which implies a somewhat stiffer numerical representation; however, the agreement is reasonable for continuing the stress and moment analysis.

Table 2. Comparison of natural frequency and time period for analytical and STAAD.Pro values.

Mode shape no.	Analytical natural frequency (cycles/sec)	Analytical time period (sec)	STAAD.Pro natural frequency (cycles/sec)	STAAD.Pro time period (sec)
1	35.08	0.0285	39.906	0.0251
1	35.08	0.0285	39.906	0.0251
2	47.65	0.0209	51.98	0.0192
3	49.84	0.02	52.37	0.019

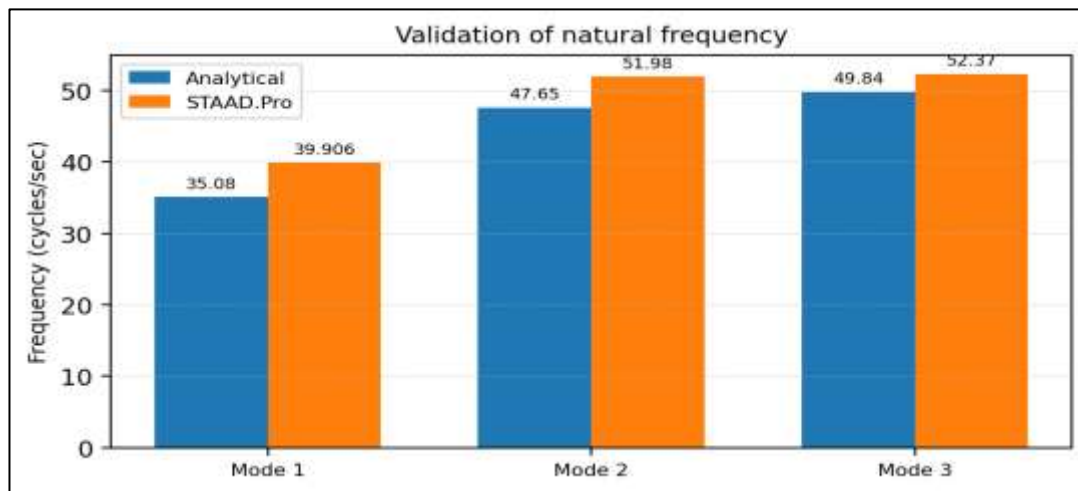


Figure 2. Analytical and STAAD.Pro natural frequency comparison for the first three modes.

7. Results and Discussion

The results obtained from STAAD.Pro are interpreted in terms of stress distribution, shear stress components, bending moment components, natural frequency and time period. The analysis compares single hopper and double hopper silos, studies the effect of hard, medium and soft soil, and evaluates the response of rectangular and circular hopper configurations. The result discussion below preserves the numerical values reported in the analysis and presents them in research paper form.

7.1 Stress Response of Single and Double Hopper Silos

The edge regions and hopper-wall junctions are critical because load transfer is concentrated around these geometric discontinuities. The maximum absolute stress developed in the single hopper silo is 4.80 MPa, whereas the corresponding value for the double hopper silo is 4.41 MPa. This indicates that the double hopper arrangement improves load distribution and reduces the maximum absolute stress by about 8.1%.

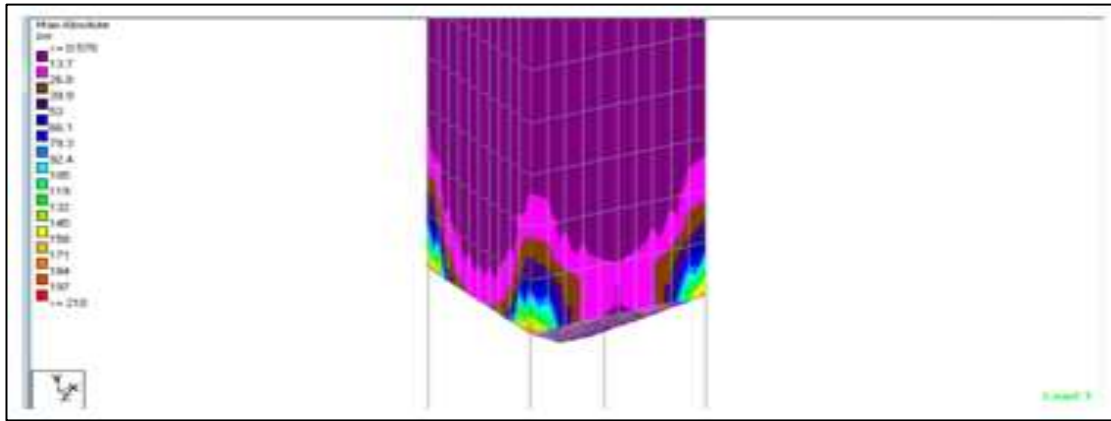


Figure 3. Maximum absolute stress distribution in single hopper silo.

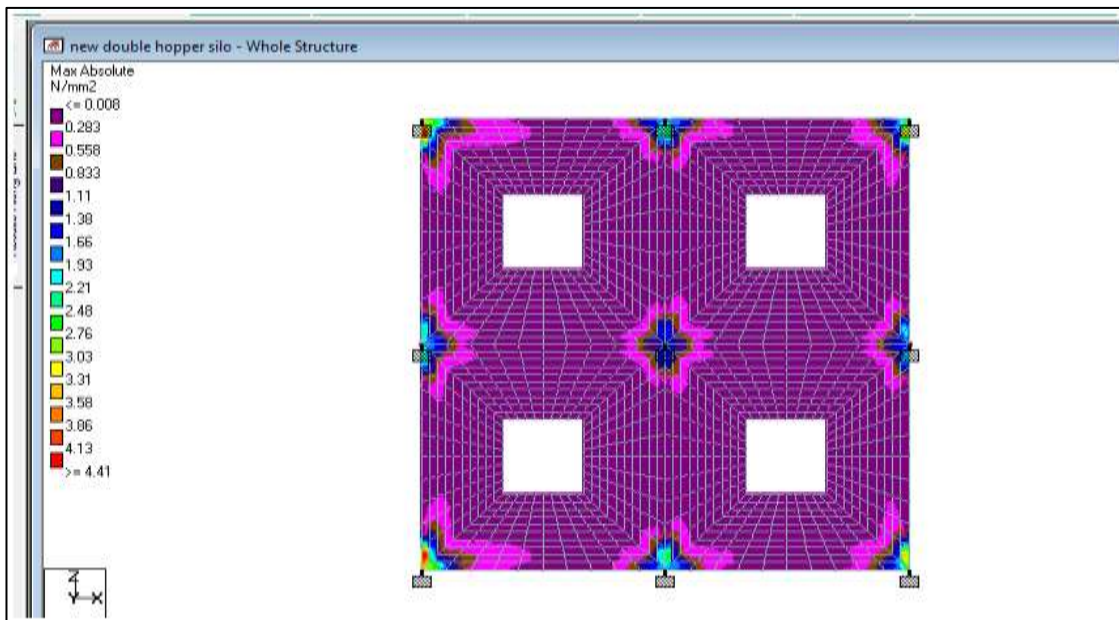


Figure 4. Maximum absolute stress distribution in double hopper silo.

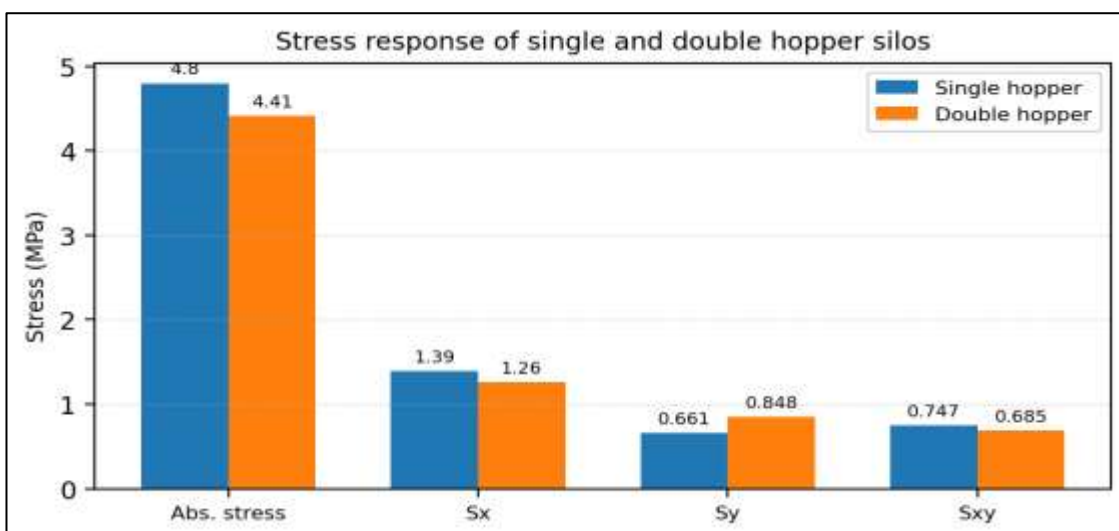


Figure 5. Comparative stress response of single and double hopper silos.

For X-direction shear stress, the single hopper silo develops 1.39 MPa while the double hopper silo develops 1.26 MPa. Therefore, the double hopper system shows a lower S_x demand. In the Y-direction, the single hopper silo develops 0.661 MPa, whereas the double hopper silo develops 0.848 MPa. This shows that the double hopper arrangement reduces some

stress components but increases Y-direction shear demand due to redistribution of load through multiple hopper openings. The S_{xy} value reduces from 0.747 MPa in the single hopper silo to 0.685 MPa in the double hopper silo, indicating a reduction in combined shear effect.

7.2 Moment Response of Single and Double Hopper Silos

The bending moment comparison shows a direction-dependent response. The maximum M_x value reduces from 11.6 in the single hopper silo to 6.81 in the double hopper silo, which clearly shows the advantage of the double hopper arrangement for X-direction bending. However, the maximum M_y value increases from 9.13 to 13.82 and the maximum M_{xy} value increases from 7.08 to 9.55 in the double hopper silo. This means that the double hopper configuration reduces X-direction bending but creates higher Y-direction and twisting moment demand.

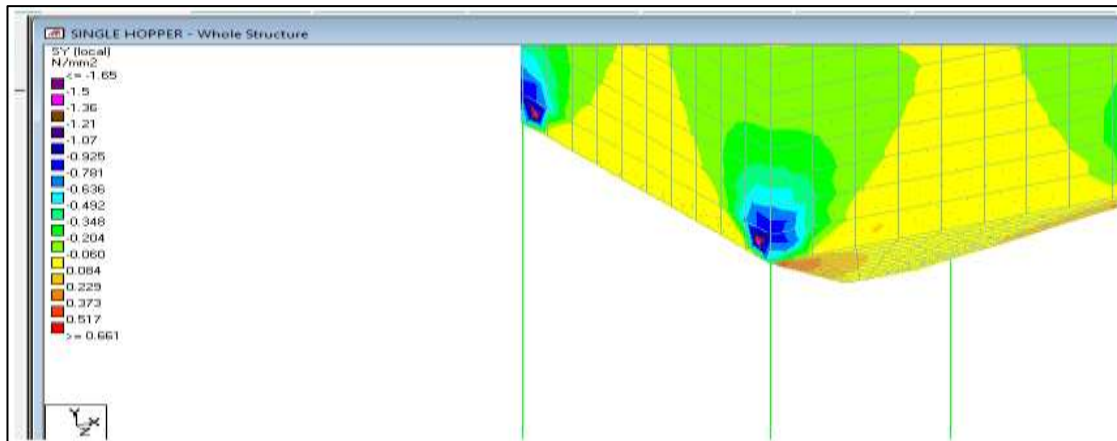


Figure 6. Representative shear/moment contour near hopper region from STAAD.Pro output.

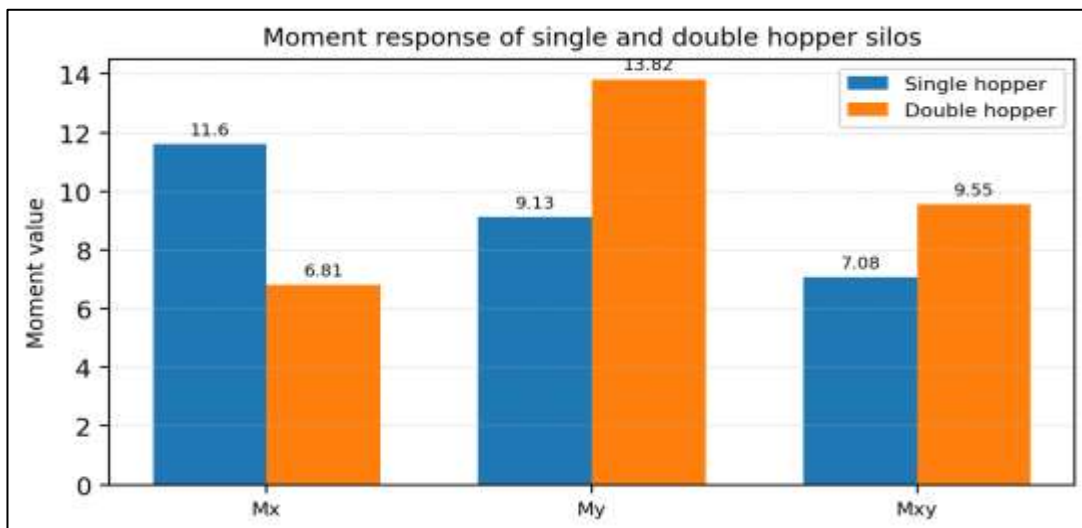


Figure 7. Comparative moment response of single and double hopper silos.

From a design point of view, this directional variation is important because a configuration that reduces one response parameter may still increase another. The double hopper silo therefore requires special attention to Y-direction bending reinforcement and torsional detailing around hopper-wall junctions, while the single hopper silo requires greater attention to X-direction moment and absolute stress at the edge region.

7.3 Effect of Soil Condition on Silo Response

The analysis under different soil conditions shows a consistent increase in stress and moment values as the soil changes from hard to medium and soft. The maximum absolute stress increases from 4.80 MPa under hard soil to 6.33 MPa under medium soil and 7.38 MPa under soft soil. Similarly, the maximum S_x value increases from 1.39 MPa to 1.91 MPa and 2.26 MPa. The S_y value increases from 0.661 MPa to 0.869 MPa and 1.01 MPa, while S_{xy} increases from

0.747 MPa to 0.874 MPa and 0.969 MPa. These results confirm that soft soil produces a more critical response under seismic loading.

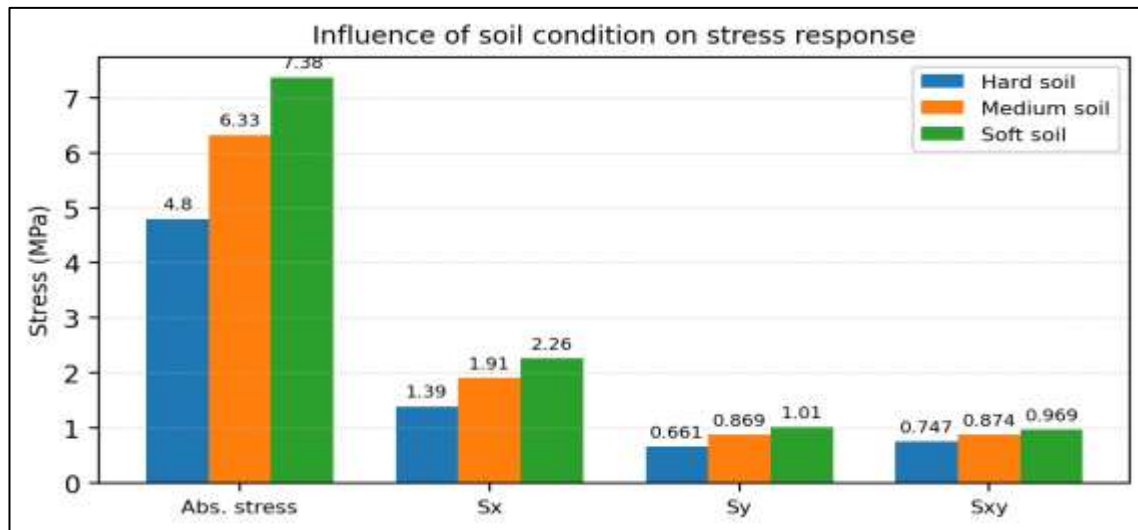


Figure 8. Effect of soil condition on absolute and shear stress response.

The moment response also follows the same trend. M_x increases from 11.6 for hard soil to 16.1 for medium soil and 19.2 for soft soil. M_y increases from 9.13 to 17.1 and 22.4, while M_{xy} increases from 7.08 to 10.3 and 12.6. Therefore, foundation soil condition is a key factor in seismic silo design, and silos founded on soft soil require conservative design checks, careful reinforcement detailing and appropriate foundation stiffness assessment.

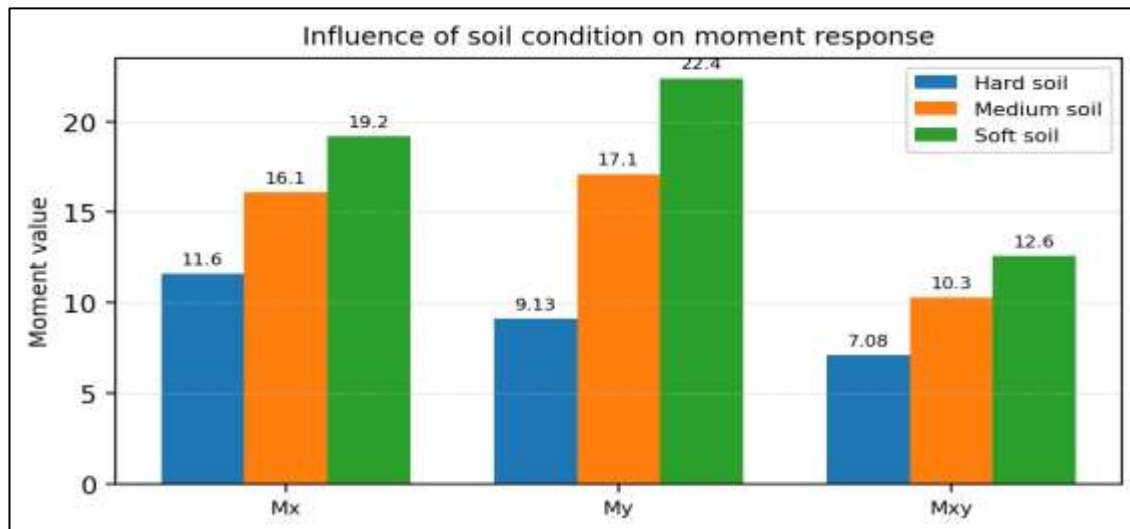


Figure 9. Effect of soil condition on bending moment response.

7.4 Natural Frequency and Time Period

The single hopper silo shows higher frequencies in the first three modes than the double hopper silo. For the single hopper silo, the first three natural frequencies are 103.839, 117.572 and 117.572 cycles/sec with time periods of 0.00963, 0.00851 and 0.00851 sec. The fourth, fifth and sixth mode frequencies are 495.534, 503.093 and 525.103 cycles/sec. These high values indicate comparatively higher stiffness and faster dynamic response.

Table 3. Natural frequency and time period of single hopper silo.

Type	Mode no.	Natural frequency (cycles/sec)	Time period (sec)
Single Hopper Steel Silos	1	103.839	0.00963
	2	117.572	0.00851
	3	117.572	0.00851
	4	495.534	0.00202

Type	Mode no.	Natural frequency (cycles/sec)	Time period (sec)
	5	503.093	0.00199
	6	525.103	0.0019

For the double hopper silo, the first three natural frequencies are 81.599, 94.827 and 97.572 cycles/sec with time periods of 0.01226, 0.01055 and 0.01025 sec. The first three frequencies of the double hopper silo are lower than those of the single hopper silo, indicating greater flexibility in the initial modes. This confirms that hopper arrangement affects global stiffness and dynamic behaviour.

Table 4. Natural frequency and time period of double hopper silo.

Type	Mode no.	Natural frequency (cycles/sec)	Time period (sec)
Double Hopper Steel Silos	1	81.599	0.01226
	2	94.827	0.01055
	3	97.572	0.01025
	4	572.261	0.00175
	5	578.946	0.00173
	6	583.21	0.00171

7.5 Rectangular and Circular Hopper Comparison

The comparison between rectangular and circular hopper configurations shows that circular geometry gives lower shear and moment demand. The maximum S_x value reduces from 1.39 MPa in the rectangular hopper silo to 0.707 MPa in the circular hopper silo. The maximum S_y value reduces from 0.661 MPa to 0.148 MPa and the maximum S_{xy} value reduces from 0.747 MPa to 0.318 MPa. The moment response also reduces considerably, with M_x decreasing from 11.6 to 1.52, M_y decreasing from 9.13 to 4.24 and M_{xy} decreasing from 7.08 to 3.78. This confirms that circular hopper geometry provides a more uniform stress distribution and better seismic resistance than the rectangular hopper configuration.

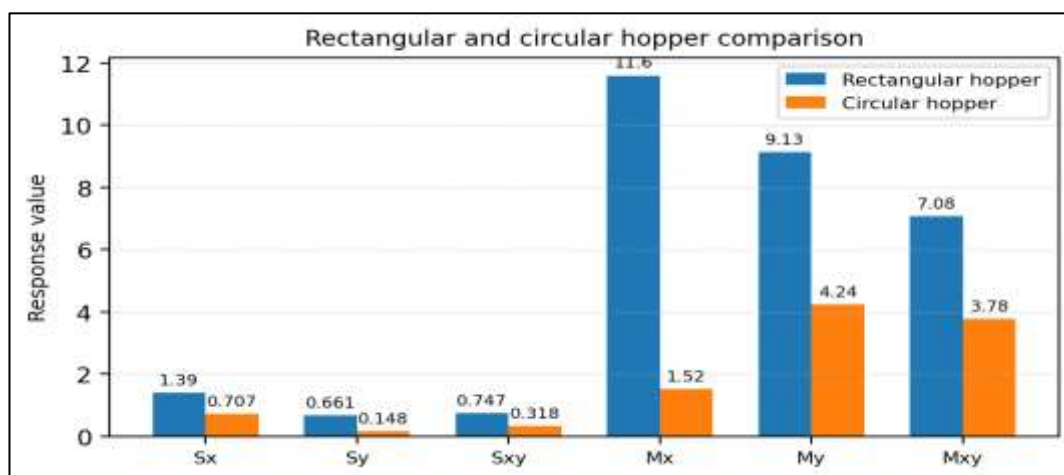


Figure 10. Rectangular and circular hopper comparison based on reported results.

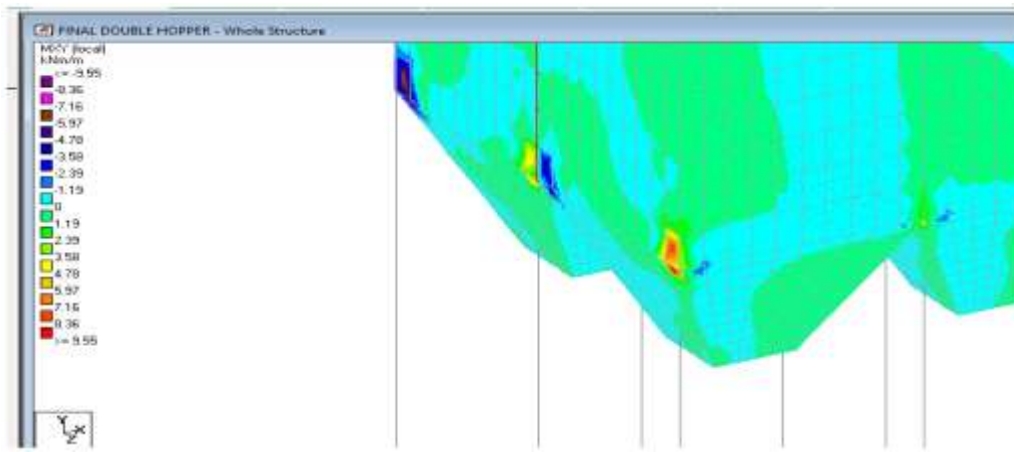


Figure 11. Representative STAAD.Pro contour output used for response comparison.

7.6 Representative Finite Element Contour Outputs

Additional STAAD.Pro contour plots are included to support the numerical interpretation of shear stress and bending moment distribution. These outputs show that the stress concentration is generally located near hopper corners, support regions and wall-hopper junctions. The contours also show that local response is more critical near openings and changes in stiffness, which confirms the need for careful detailing of reinforcement around these locations.

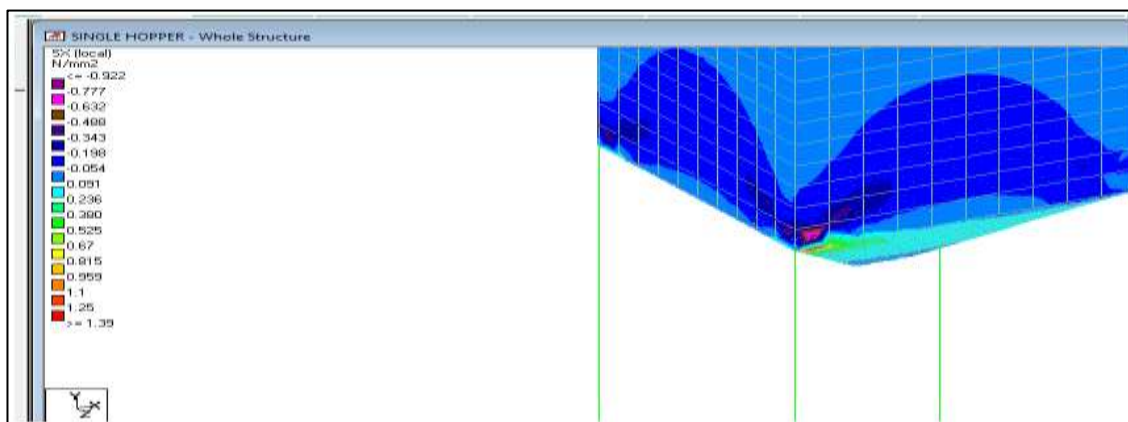


Figure 12. Representative contour output for the single hopper silo response.

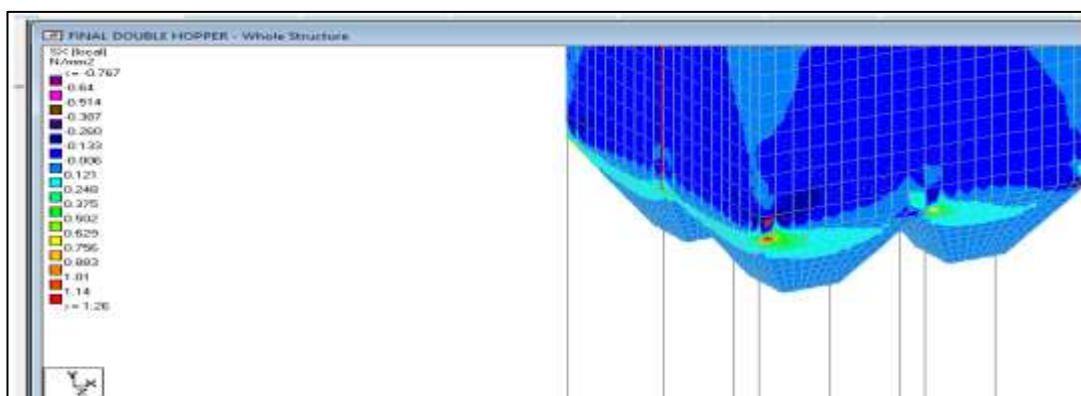


Figure 13. Representative contour output for the double hopper silo response.

The following additional plots show the directional variation of response parameters. In seismic analysis, the directional distribution of stress and moment is important because the critical design case may not be governed by a single global maximum. Instead, local shear, bending and twisting actions must be checked simultaneously.

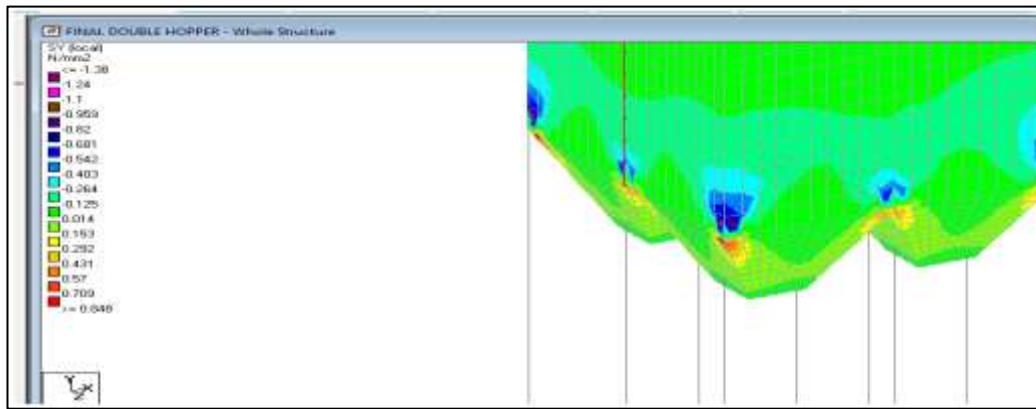


Figure 14. STAAD.Pro contour output showing local response around hopper-wall connection.

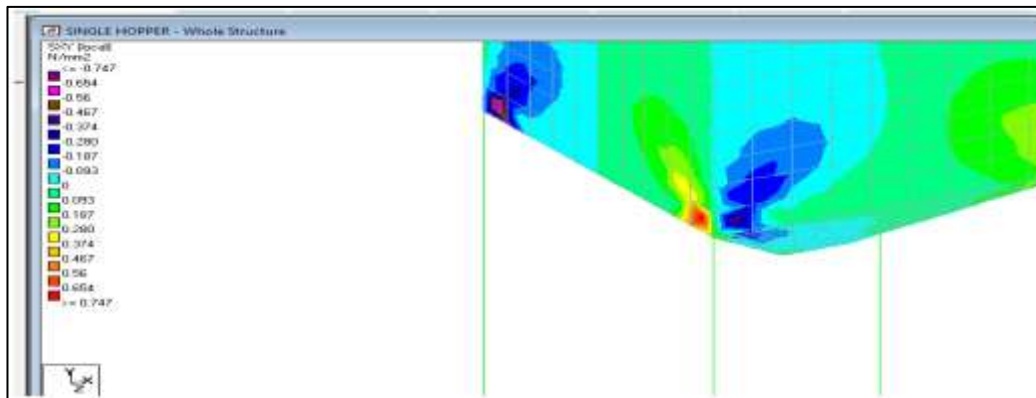


Figure 15. STAAD.Pro contour output showing directional stress distribution.

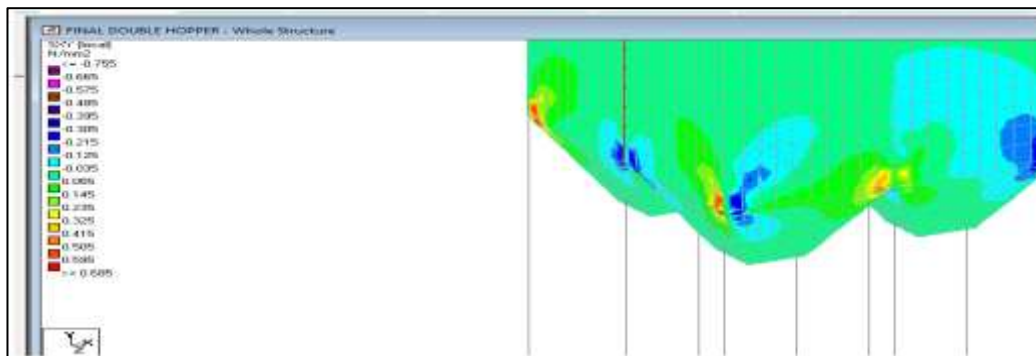


Figure 16. STAAD.Pro contour output showing stress redistribution under applied loading.

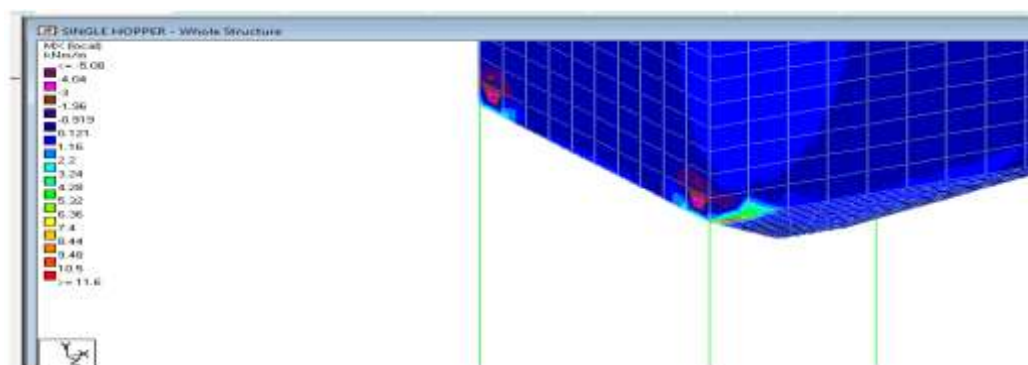


Figure 17. STAAD.Pro contour output showing moment concentration near hopper region.

These visual results support the numerical observation that single hopper and double hopper systems behave differently under seismic and stored material loading. The images also support the conclusion that changes in hopper geometry and support stiffness influence the transfer of load from the wall to the base and must be included in design assessment.

8. Discussion

The overall results show that silo response is controlled by hopper configuration, soil condition and plan geometry. The double hopper silo reduces maximum absolute stress, S_x and S_{xy} stress, and X-direction bending moment compared with the single hopper silo. However, the same configuration increases S_y , M_y and M_{xy} values, which means that the design cannot be judged using only one response parameter. A complete design check must consider all shear and moment components along with stress concentration at the hopper-wall junction. The soil condition study is particularly important for seismic design. Soft soil produces the highest stresses and moments because lower soil stiffness and seismic amplification increase structural demand. Therefore, design of silos on soft soil should include conservative load combinations, stronger foundation checks and enhanced reinforcement at critical wall and support regions. The comparison of rectangular and circular hoppers indicates that circular geometry is structurally more efficient because it reduces stress concentration and provides smoother pressure transfer.

9. Conclusions

The study concludes that single and double hopper silo configurations show different stress, moment and dynamic behaviours under self-weight, stored material pressure and seismic loading. In this study single and double hopper steel silos are analyzed under the influence of self-weight, pressure on vertical wall and seismic load. It was observed that maximum displacement along X-direction and Z-direction is reduced by 15-20% in single hopper silo. But displacement along in Y-direction i.e. along gravity direction 20 % less in double hopper silo as compared to single hopper silo. However nodal rotation remains nearly same indicates that the torsion movement due to accidental eccentricity will be same in both cases. Natural frequency for first three modes is considerably 17% less and hence time period is more for double hopper steel silo.

The numerical results further show that double hopper arrangement reduces absolute stress and X-direction shear and moment, but increases Y-direction shear and moment demand. The soil condition study confirms that soft soil is the most critical condition for silo response. The circular hopper comparison shows lower shear and moment values than the rectangular hopper, making circular geometry more favourable for seismic and stored material pressure resistance. Overall, finite element modelling in STAAD.Pro is effective for identifying critical stress zones and for improving the safety and reliability of silo structures under Indian seismic zone conditions.

10. Future Scope

Future work may include detailed finite element analysis of the ROM silo at the mine to predict service life and progressive deterioration under repeated filling, discharge and seismic events. The present numerical model can be extended by including nonlinear material behaviour, soil-structure interaction, staged construction effects, different storage levels, dynamic time-history analysis and actual site-specific earthquake records. Experimental or field monitoring data may also be used to validate the numerical model and improve confidence in stress concentration and failure-point prediction. Further research can compare reinforced concrete, steel and composite silo alternatives under identical storage and seismic conditions to develop economical and performance-based design recommendations.

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