Seismic and Wind Resistance Numerical Simulation Analysis of Cement Silos Based on SAP2000

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Abstract. The large enamel-assembled storage silo, as an emerging industry, is currently in a period of rapid development. Its unique bolted construction technology and excellent enamel anti-corrosion technology have led to the gradual application of enamel-assembled silos in areas such as military storage, strategic material reserves, municipal wastewater treatment, and biogas fermentation. As a new type of silo, the stable structure and the high economic efficiency are the key factors ensuring its explosive growth in applications. This paper aims to comprehensively evaluate the structural performance of material silos under varying load conditions and verify their safety to ensure the robustness and reliability of the design. The SAP2000 simulation software is employed for the analysis, simulating the stress states of the material silos under static conditions, constant load + storage load + seismic conditions, and constant load + wind load conditions. Through multiple load combinations, the stress states of the material silos under various conditions are validated. Under static conditions, the maximum stress occurs at the bottom wall plate of the silo wall, reaching 84.8 MPa, showing consistency throughout the entire structure and presenting an axial increasing trend. Regarding displacement characteristics, the most significant stress concentration and deformation occur in the area of the silo structure which is subjected to the load. Under constant load + storage load + seismic conditions, the overall stress of the silo wall decreases non-linearly from the bottom fixed constraint, with stress fluctuations occurring at the cement-poured fixed constraint, which is the position of the maximum static water pressure force. Under constant load + wind load conditions, the vertical stress values of the silo structure are uniformly distributed, with differences in circumferential stress distribution—compression on the windward side and tension on the leeward side, reaching up to 100 MPa, with deformation decreasing from top to bottom. Considering material load, wind load, seismic load, and other possible conditions, this paper concludes the stress and strain conditions of the material silo under different working conditions, which helps optimize and improve the structure of existing material silos and promote the development of related fields.

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1 Introduction

Material silos are indispensable equipment in modern industrial production, widely used in mining, chemical, metallurgical, building materials, grain, and other industries. Their primary function is to store and manage various solid or powdered materials, ensuring the continuity and stability of the production process. With the continuous development of industrial technology and the improved level of automation, the design and management of material silos have become increasingly complex and important.

Unlike traditional silo design, modern silo design continues to innovate, adopting new structural forms such as large-span space structures, prestressed structures, and composite structures. These structural forms significantly improve space utilization, reduce self-weight, and enhance seismic performance. However, the design and construction of these new structures are more challenging, requiring advanced computational methods and construction techniques, where traditional design methods lack the experience and technology to effectively handle modern silo design tasks.

Furthermore, with the advancement of computer and information technologies, modern silo design is increasingly digitalized, intelligent, and automated, making the design process more precise, efficient, and convenient. In comparison, traditional design methods rely on manual calculations and drafting, making it difficult to adapt to the changes brought by these technological advancements. Traditional methods also have limitations in optimization design and simulation analysis, unable to fully capitalize on the advantages of modern technology.

In summary, traditional design methods have many shortcomings when addressing the complexity and diverse needs of modern material silos. To achieve efficient, safe, and economical design goals, more advanced design concepts, methods, and technologies must be employed.

By using structural analysis simulations, the stress situation of material silos under different working conditions can be simulated without carrying actual experiments, enabling further analysis of the stress distribution, deformation, and failure types of the structure. Such method can improve design accuracy and reliability while saving a significant amount of time and cost. Internationally, research on the stress analysis of material silos has made significant progress. Many research institutions and universities abroad have conducted numerous simulation studies, focusing on the stress distribution, deformation laws, and failure mechanisms of material silos under static and dynamic loads. For example, J. Jake's research on the pressure distribution of material silo buildings on the ground concluded the influencing factors and corresponding pressure distribution under different working conditions [1]. D.M. Walker's study on dust flow stress distribution in hopper systems derived the approximate stress of granular materials or powders flowing in hopper systems and provided key factors to ensure continuous gravity flow [2]. A.W. Jenike's research on load distribution design under different conditions analysed the initial load, flow load, and switch load that should exist in material silos [3]. Jenike also explored the stress distribution laws of bulk materials and applied the principle of minimum recoverable strain energy in the pressure field, ending up creating multiple formulas [4]. In China, with the acceleration of the industrialization process, the design and analysis of material silos have also received increasing attention. Domestic research mainly focuses on the few following aspects: first, using finite element method to analyse the static stress of material silos and study the impact of different materials and silo structures on stress distribution; second, considering the impact of dynamic loads (such as earthquakes and winds) on material silos to explore the structural safety under complex working conditions; third, combining experimental data to verify the accuracy and reliability of simulation models to provide scientific evidence for actual engineering design.

This paper aims to systematically study the stress situation of material silos under different working conditions using the SAP2000 structural analysis method. The specific aspects include:

1. Wind Resistance Analysis: Simulating the stress situation of material silos under strong wind conditions, analysing the impact of different wind speeds and directions on the structure of material silos, and evaluating their wind resistance.

2. Seismic Resistance Analysis: Studying the dynamic response of material silos under seismic loads, analysing the impact of different earthquake intensities and frequencies on the structure of material silos, and exploring their seismic capacity and failure types.

The studies above will provide theoretical support and reference for the optimization design and safety assessment of material silos, helping to improve the structural safety and operational reliability of material silos, promoting the technological progress and application development in related fields. The research results can be applied not only to the transformation and optimization design of existing material silos but also to provide scientific guidance for the design of new material silos, showing wide engineering application value and profound socio-economic benefits.

2 Model Establishment

2.1 Digital Model Establishment of Material Silos

This paper uses the SAP2000 software for precise modelling, focusing on a storage silo with specific geometric dimensions and construction characteristics. The height of the material silo is designed to be 19 meters to ensure sufficient capacity to meet storage needs, and the bottom diameter is set at 6.25 meters, providing stable support for the material silo. Q355B steel is a type of lean alloy high-strength structural steel that features high strength and toughness. It is widely used in industries such as construction, manufacturing, and shipbuilding due to its excellent mechanical properties, corrosion resistance, and workability. Therefore, Q355B is selected as the material for the silo, following the national standard of the People's Republic of China "Lean Alloy High Strength Structural Steel" GB/T 1591-2018 with specific parameters as shown in Table 1, Table 2 and Table 3:

Table 1. Chemical Composition of Q355B Steel [5]

Element	C	Si	Mn	S	P	Cr	Ni	Cu
Mass Fraction（%）	≤0.24	≤ 0.55	≤ 1.60	≤ 0.035	≤ 0.035	≤ 0.30	≤ 0.30	≤ 0.30

Table 2. Mechanical Performance Indicators of Q355B Steel [5]

Indicator	Yield Strength	Tensile Strength	Elongation (Longitudinal)	Elongation (Transverse)
Requirement	≥355MPa	≥470MPa	≥22%	≥20%

Table 3. Model Parameters of Q355B Steel [5]

Model Parameter	E/GPa	v	$\rho/(kg{\cdot}m^3)$
Value	206	0.30	7850

The established model is shown in Figure 1.

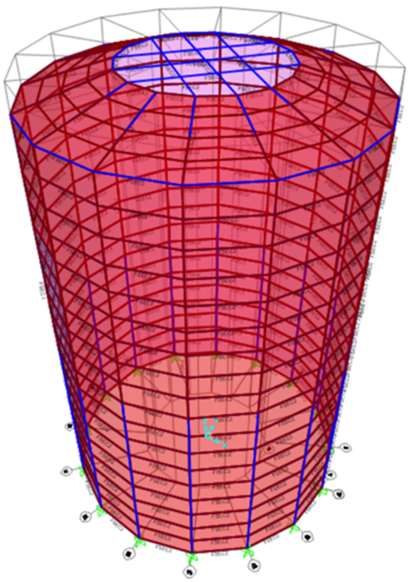


Fig. 1. Material Silo Model

In terms of construction, the silo body adopts a multi-layer steel plate structure as shown in Figure 2. Each layer of steel plate has different thicknesses to meet the strength and stiffness requirements of different areas. These steel plates are connected by carefully designed bolt flanges to ensure the tightness and stability of the structure. This connection method not only improves the overall stability of the silo but also makes maintenance and replacement work more convenient in the future.

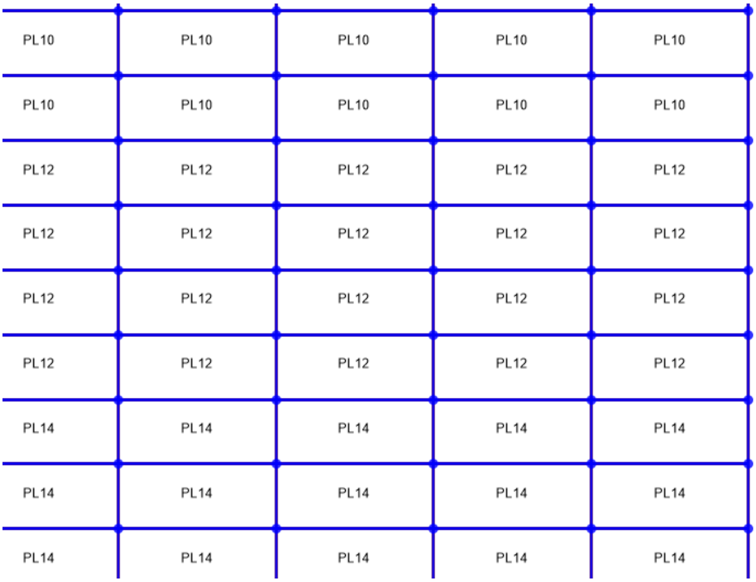


Fig. 2. Steel Plates of Different Thicknesses

At the bottom of the material silo, a hinged fixing method is used to secure it firmly to the ground. This design takes the bearing capacity of the ground into account and ensures that the silo can have some flexibility when subjected to external forces, thereby avoiding damage due to stress concentration.

In addition, the top of the material silo adopts a conical opening design, which not only facilitates the loading and unloading and flow of materials but also helps prevent caking or blockage during storage. The conical opening design also optimizes the overall structure of the material silo, making it more in line with mechanical principles, improving structural stability and safety [6].

2.2 Application of Storage Load

To begin with, it is necessary to clarify the type of material silo in the study. According to the conventional definition in the engineering field, material silos can be classified based on the ratio of their height to diameter. Specifically, when the ratio of height to diameter is greater than 1.5, it is called a deep silo; when the ratio is less than or equal to 1.5, it is called a shallow silo.

After detailed analysis and comparison, the material silo in the study is determined to be a shallow silo. To more accurately simulate the actual state of materials in the shallow silo, this paper uses the material load application tool in the SAP2000 CiSApps.

Through this tool, specified storage pressure loads can be applied based on the actual properties and storage conditions of the material. As for the selection of the loading position, the silo wall is selected as the main force-bearing surface because, in shallow silos, the silo wall often bears the majority of material pressure. In the load mode setting, the storage load mode is chosen to simulate the actual stress situation of the material during storage. Finally, in the selection of material height, it is ensured that the selected top surface is equal to the cylindrical surface of the silo to ensure the accuracy of the simulation results.

2.3 Establishment of Wind Load Model

Wind loads have complex and multifaceted effects on buildings, especially on large storage facilities like material silos. Material silos have wide side surfaces, and their tops are usually conical, making them particularly sensitive to wind loads [7].

When wind acts on a material silo, its action surface mainly includes the side walls of the silo and the conical structure at the top. To accurately simulate and analyse the impact of wind loads on the material silo, this paper uses a method called "virtual surface + uniformly distributed surface load on the frame." This method first defines a virtual surface that covers the windward surface of the material silo to capture the wind force. Then, through specific calculations and analyses, these forces are uniformly distributed to the frame structure of the material silo, known as "uniformly distributed surface load." During the load transfer process, the wind load is transmitted unidirectionally, meaning that the wind force will only transfer to the frame of the material silo in a specific direction without reverse transmission or deviation [8].

It is worth noting that the value of uniformly distributed surface load is not set positive or negative arbitrarily but are determined based on two key factors. The first factor is the actual wind direction, i.e., from which direction the wind is blowing; the second factor is the load direction set in the program, which is usually based on the building's coordinate system or the engineer's pre-setting. When the actual wind direction is consistent with the load direction in the program, the uniformly distributed surface load is positive; otherwise, when the two directions are opposite, the uniformly distributed surface load is negative. Such setting ensures the accuracy and reliability of the analysis results, providing an important guarantee for the safe design and operation of the material silo. In summary, this paper selects a structural width of 12.5m, a basic wind pressure of 0.45kN/m^2, a damping ratio of 0.02, and basic periods and mode coefficients using modal analysis to establish the wind load model.

2.4 Establishment of Seismic Model

This paper calculates the seismic action through the bottom shearing force method, i.e., considering automatic seismic loads in SAP2000. It mainly includes two operations: modifying the automatic seismic load parameters and defining the mass source. The mass source defaults to using "unit mass and additional mass" for calculation, but for this model, the self-weight of the material and loading equipment is applied to the structure as a load, and although their stiffness is not considered in the analysis, the mass generated by their self-weight affects the stiffness of the structure. The definition of the mass source corresponds to the representative value of gravity load in the Chinese National Standard, considering the constant load 1 times and the live load 0.8 times.

In structural safety design, the accurate application of seismic loads is crucial, as it directly relates to the safety performance and seismic capacity of the building. In practical operation, the primary focus for the application of seismic loads is the X-direction seismic load because seismic waves often act in different directions, and the X-direction is usually one of the main directions considered in the structural design of buildings [9].

When applying seismic loads, this paper not only considers the amplitude and frequency of seismic waves but also a series of coefficients related to earthquakes. These coefficients include but are not limited to the seismic impact coefficient, which is a quantitative indicator used to measure the impact of an earthquake on the structure, and is significant for evaluating the seismic performance of the structure. Additionally, the seismic fortification intensity is also a crucial factor, providing specific seismic fortification requirements for structural design based on the seismic activity and potential seismic hazards of the building's location.

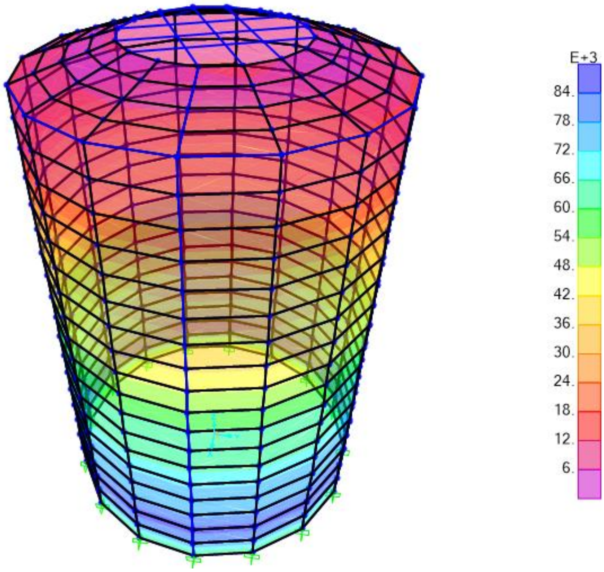
At the same time, the damping ratio period is also an important factor to consider when applying seismic loads. The damping ratio describes the energy dissipation capacity of the structure under seismic action, while the period reflects the natural vibration characteristics of the structure, with the damping ratio set at 0.02[10]. By comprehensively considering these parameters, this paper can more accurately simulate the effect of seismic action on the structure and apply seismic loads that match the actual working conditions.

3 Simulation Results and Analysis

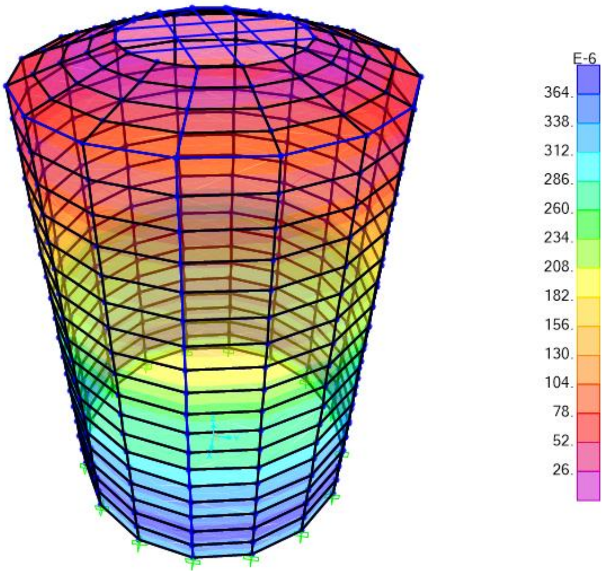
3.1 Numerical Analysis Results Under Static Conditions

To explore the mechanical behaviour of the tank under static conditions, this paper first needs to meticulously analyse the stress distribution and displacement characteristics of the entire structure under the combined action of constant load and storage load. As shown in Figure 3, the stress and displacement nephogram under this composite load are straightly depicted, providing critical data support for subsequent mechanical analysis.

In terms of stress distribution, the maximum stress is observed at the bottom wall plate of the silo wall, with a specific value of 84.8 MPa. This value is not only lower than the yield strength of the tank material but also shows consistency throughout the entire structure of the silo. What is particularly noteworthy is that the obvious axial increasing trend in the stress distribution, increasing from the top to the bottom of the silo. This distribution characteristic meets the expected requirements of the tank strength under design conditions, further validating the rationality of the structural design of the silo.



a) Stress Nephogram



b) Displacement Nephogram

Fig. 3. Stress-Strain Nephogram under Constant Load + Storage Load Conditions

In terms of displacement characteristics, the tank deforms under the combined action of constant load and storage load. At this time, the maximum deformation of the tank is only 3.64 cm, far below the allowable maximum deformation limit designed, indicating that the tank can maintain good stability under such loads. Further analysis reveals that due to the fixed support of the bottom bracket, the maximum deformation occurs at a position 1800 mm from the bottom wall plate of the tank to the ground. This position happens to be the area where stress concentration and deformation are most significant when the structure is subjected to load. Focusing on and optimizing this area can effectively improve the overall bearing capacity and stability of the tank.

3.2 Numerical Analysis Results Under Extreme Conditions

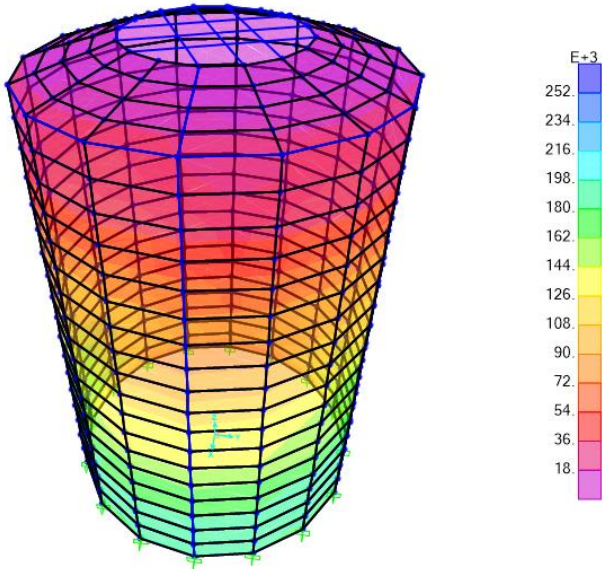
In structural design, simulating extreme conditions is essential to replicate possible abnormal real-world applications' conditions, such as earthquakes and strong winds. These extreme conditions pose significant challenges to the stability of the tank and its internal materials. Specifically speaking, when seismic waves act on the tank, the materials will be subjected to dynamic loads, producing significant impacts on the tank walls in a short time [11][12]. Similarly, when the tank is subjected to lateral wind loads, the side pressure exerted by the wind significantly increases the stress on the tank walls and their structure. Under these extreme conditions, the stress level that the tank endures may exceed the design ultimate strength, causing a risk of partial collapse. Such a collapse could lead to material leakage and potentially severe impacts on the surrounding environment and personnel safety. Therefore, simulating and analysing the stress of the tank under these two extreme conditions is of great practical significance.

In the following sections, this paper will simulate the stress situation of the tank under seismic and strong wind conditions separately. Through precise calculations and analyses, important data such as stress distribution and deformation of the tank under extreme conditions will be obtained. These data will provide a crucial basis for optimizing the structural design of the tank, helping engineers design safer and more stable tank structures to prevent accidents in actual engineering applications.

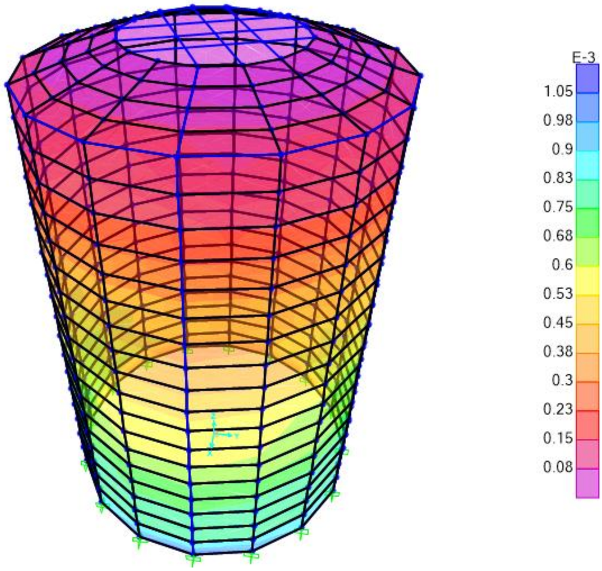
3.2.1 Constant Load + Storage Load + Seismic Condition.

From Figure 4, it can be seen that the overall stress of the tank wall decreases from the bottom fixed constraint. However, the entire decreasing process is not linear, with significant stress fluctuations occurring at a position 1800 mm from the bottom, due to the fixed constraint of the cement-poured base, which is also the position of the maximum static water pressure force. The tank's thin-walled structure subjected to static water pressure will have tensile deformation within the elastic limit of the steel plate, meaning the diameter of the tank will be slightly larger than the theoretical design value. However, since the bottom of the tank is fixed, the expanded tank diameter is restricted, leading to significant deformation fluctuations at the bottom of the tank, making it more noticeable than other positions on the tank wall. As the height of the tank wall increases, there is a small increase in stress near the top of the tank, due to the radial tension exerted by the inflating inner and outer membranes of the tank top. From Figure 4 a) the stress and b) deformation nephogram of the tank wall, it can be seen that under design conditions, the stress and deformation of the tank wall show a step-like circumferential uniform distribution, overall presenting an increasing trend from top to bottom. The maximum stress is located at the position where the maximum deformation of the wall plate occurs, with an analytical stress of 252 MPa and a deformation of 10.5

cm. From the overall stress and deformation, the stress intensity and deformation of the tank under design conditions are within the safe range, and the entire tank remains in a stable structural state.



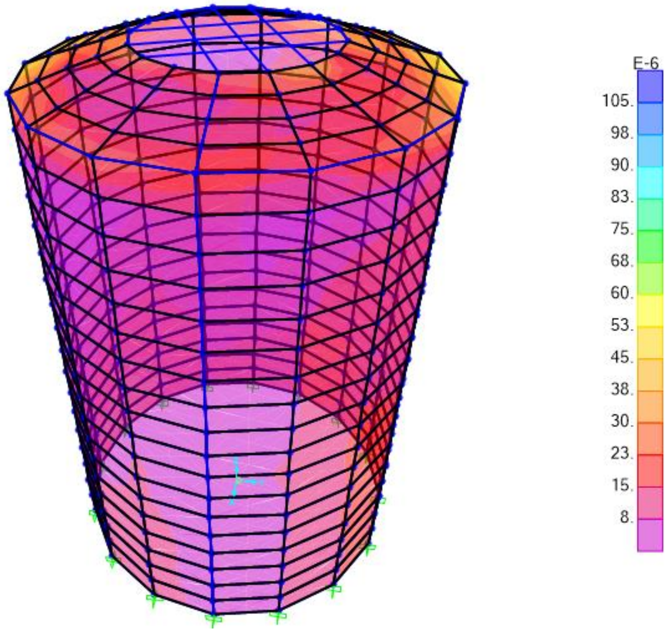
a) Stress Nephogram



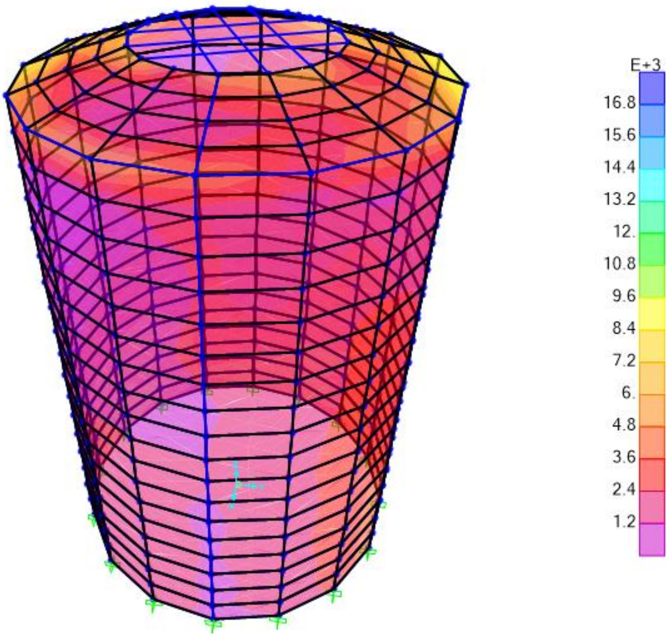
b) Displacement Nephogram

Fig. 4. Stress-Strain Nephogram under Constant Load + Storage Load + Seismic Conditions

3.2.2 Constant Load + Wind Load Condition.



a) Stress Nephogram



b) Displacement Nephogram

Fig. 5. Stress-Strain Nephogram under Self-Weight + Wind Load Conditions

In analysing the mechanical characteristics of the tank under wind pressure in an unloaded state, a series of important phenomena can be observed from the stress and deformation nephogram in Figure 5. Firstly, from the vertical direction, the stress of the tank is generally uniformly distributed, without significant differences. However, when focusing on the circumferential stress distribution, it is evident that there are significant differences between the stress values on the windward and leeward sides. Specifically, under wind pressure, the windward side is subjected to greater compressive stress, while the leeward side is subjected to tensile stress accordingly. This uneven stress distribution poses challenges to the structural integrity and stability of the tank.

Further analysis reveals that the maximum circumferential stress reaches 100 MPa, which, although not reaching the material's ultimate strength, is a noteworthy stress level. In the design and manufacturing process of the tank, such stress level must be fully considered to ensure that the tank can maintain sufficient stability and safety under wind pressure.

When examining the deformation characteristics, it is observed that, due to the bottom of the tank being anchored to the ground, the distribution of deformation follows a specific pattern. Specifically, the deformation gradually decreases from the top to the bottom of the tank, indicating that the tank undergoes overall bending deformation under wind pressure. Notably, the maximum deformation is observed at the top edge of the tank, with a specific value of 16.8 cm. Although this deformation is within acceptable limits, it may still have a certain impact on the operational performance of the tank.

In summary, when the tank is subjected to wind pressure in an unloaded state, the windward side experiences compression while the leeward side is under tension, resulting in significant differences in the circumferential stress distribution, with the maximum stress reaching 100 MPa. Additionally, the deformation decreases progressively from the top to the bottom, with the maximum deformation occurring at the top edge. These mechanical characteristics provide important reference points for the design and manufacturing of the tank and merit further in-depth study and investigation.

4 Conclusion

This paper uses the SAP2000 software to conduct a comprehensive stress analysis of material silos, considering multiple working conditions such as material load, wind load, and seismic load. The analysis of the combined effects in the static state shows that the increase in material load significantly affects the overall structural stress distribution of the material silo, especially at key connection points and supporting areas, with a maximum stress of 252 MPa and deformation of 10.5 cm. Under seismic action, the structure shows favourable stability, and can effectively respond to dynamic loads despite significant impacts. Additionally, analysing the impact of wind load in an unloaded state reveals that wind load has a lesser impact on the material silo compared to seismic impact, with compressive stress on the windward side and tensile stress on the leeward side, and a maximum stress of 100 MPa.

The methods adopted in this paper include not only traditional load analysis but also a particular check of wind resistance in an unloaded state, which is relatively rare in analysing the stress behaviour of material silos. The innovation lies in comprehensively considering and simulating the performance of material silos under multiple dynamic and static load conditions, ensuring the reliability and robustness of their design. This helps provide a comprehensive mechanical performance evaluation for the design of material silos, especially ensuring performance under extreme conditions.

In conclusion, through the SAP2000 simulation analysis, this paper comprehensively evaluates the structural performance of material silos under different load conditions and verifies their safety under different load combinations. Through simulating multiple load combinations, the stress states of the material silos under various conditions are validated, ensuring the robustness and reliability of their design. Finally, considering material load, wind load, seismic load, and other possible conditions, the conclusions are:

1. Under static conditions, the maximum stress occurs at the bottom wall plate of the silo wall, reaching 84.8 MPa, showing consistency throughout the entire structure and presenting an axial increasing trend. Regarding displacement characteristics, the most significant stress concentration and deformation occur in the area of the silo structure subjected to the load.

2. Under constant load + storage load + seismic conditions, the overall stress of the silo wall decreases non-linearly from the bottom fixed constraint, with stress fluctuations occurring at the cement-poured fixed constraint, which is also the position of the maximum static water pressure force.

3. Under constant load + wind load conditions, the vertical stress values of the silo structure are uniformly distributed, with differences in circumferential stress distribution—compression on the windward side and tension on the leeward side, reaching up to 100 MPa, with deformation decreasing from top to bottom.

This paper employs SAP2000 simulation software to conduct a comprehensive and systematic study on the stress behaviour of material tanks under various loading conditions. Based on the research findings presented in this paper, the current state of research, and practical application in industrial production, the following areas require further investigation:

1. Further exploration of the structural performance of material tanks under more complex operating conditions: Consider the impact of seismic wave directionality and variations in wind loads on the structural stability of the tank. Seismic-induced base vibrations and wind-induced lateral forces on the tank may combine, leading to complex stress distributions and deformation. Studying the response mechanisms under these combined loads will provide a more realistic simulation of the stress conditions experienced by material tanks in actual use.

2. Consideration of the nonlinear behaviour of the tank under extreme loads: Under strong seismic or wind forces, the deformation and stress distribution of the tank may no longer follow a linear pattern. Future research should incorporate more nonlinear dynamics theories and analytical methods to simulate buckling, plastic deformation, and other potential failures in high-stress areas of the tank, which will ensure that the design can withstand the combined effects of multiple loads under extreme conditions.

3. Optimization of tank material selection: Explore the application of new lightweight, high-strength materials to further enhance the tank's impact resistance and fatigue performance. Additionally, considering the effects of different environmental factors on the tank's safety over its long-term use will contribute to extending the service life of the material tank and improving its reliability.

4. Investigation of dynamic load effects caused by the material within the tank during seismic or wind events: These effects not only increase the internal stress of the tank but also induce waves within liquids or particulate matter inside the tank. For material tanks filled with fluids or particulates, further research can explore the impact of the dynamic flow of internal materials on the structural performance of the tank, particularly regarding stress concentration or dynamic load effects in localized areas.

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