Analysis on the Dynamic Pressure of a Cylindrical Silo

WX Zhang1*, LM Yang2
1 Nantong Polytech College, Nantong, Jiangsu, 226002, China
2 School of Civil and Environmental Engineering, Hunan University of Science and Engineering, Yongzhou, Hunan, 425199, China
*Corresponding author’s e-mail: Wxzhang697608@sina.com

Abstract. In this paper, the silo wall and the storage material in the silo are considered as a whole. It is proposed that there is energy conversion between them in the process of loading and unloading. The interaction between them is analyzed and the mechanism of dynamic pressure increase is explored by referring to the method established by the earth pressure theory. At the same time, the energy principle and three-dimensional discrete element are used for theoretical analysis, and a simplified calculation method of silo lateral dynamic pressure is proposed to effectively predict the lateral dynamic pressure field and the range of pressure coefficient.

1. Introduction
Silos account for the majority of the reserves, and their performance is very important. Not only that, in other fields such as coal, metallurgy, chemical industry, light industry, etc., a large number of silos are built every year. Therefore, silos have a special position and wide application in industrial and agricultural production, modern logistics, port and wharf, etc. When the silo is unloaded, the dynamic pressure of the bulk storage on the wall is far greater than the static pressure of the bulk storage on the wall [1, 2]. Up to now, there is no widely accepted reasonable theory to accurately predict the dynamic pressure of the silo wall. According to the statistics of test results, the ratio of dynamic pressure to static pressure is also very different.

Due to the complexity of the dynamic pressure distribution of silos, the existing researches mainly focus on the influencing factors of the dynamic pressure, most of which focus on the bulk storage, and pay attention to the local influence. However, there are few researches on the mechanism of the dynamic pressure, especially on the mechanism of the interaction between the bulk storage and the silo as a whole system considering the energy conversion during the loading and unloading process, and the mechanism of the interaction between the bulk and the silo wall [3-5]. At present, most of the numerical simulation of silo pressure is based on the consideration of the storage material, not including the silo body or the deformation of the silo body. Some of them only consider the silo body and take the storage material pressure as the external load. Moreover, the simulation of silo unloading problem mainly uses two-dimensional particle discrete element, and the quantitative consideration of the influence of the storage material flow state is less. Therefore, it is necessary to consider the deformation of the silo wall, establish a three-dimensional particle discrete element model of the storage and the silo as a whole system, and carry out the numerical simulation of the influence of various storage flow patterns on the pressure [6, 7].
The pressure on the wall from the bulk storage is similar to the pressure on the retaining wall. When loading, the storage material pushes the wall outward, and the displacement of the wall is outward. The pressure of the storage material on the wall is the active pressure. During unloading, due to the continuous outflow of bulk storage materials, the warehouse wall shrinks inward, and the pressure of storage materials on the warehouse wall is passive pressure. In addition, when the bulk material is loaded into the bin, the pressure of the bulk material on the bin will cause the bin to deform outwards and have strain energy, resulting in the dynamic pressure greater than the static pressure.

2. Innovation points

(1) For the bin and storage system, the energy conversion mode in the process of loading and unloading is proposed. The dynamic unloading pressure is considered as passive pressure, which reveals the mechanism of dynamic pressure increase and makes it possible to describe it quantitatively.

(2) A three-dimensional particle discrete element model considering the deformation of the wall was established to simulate the influence of various flow patterns on the pressure.

(3) The centrifugal model is used to simulate the actual silo. The simplified calculation method of dynamic unloading pressure of silo is proposed. The dynamic unloading pressure and overpressure coefficient of silo are accurately predicted, which provides theoretical support and reference for silo design.

3. Theoretical method

Because of the variety of storage materials, the randomness of storage parameters and the change of discharge form, the dynamic pressure will be affected. The capacitance of the grain filled part and the capacitance of the dust are

\[ C_g = -\frac{e_g W L_g}{d} \]  

and

\[ C_d = -\frac{e_d W (L - L_g)}{d} \]  

respectively. The total grain volume and the effective grain level can be written as

\[ V_g = \pi r^2 \left( L_g + r \tan \theta / 3 \right) \]

\[ L_e = \pi r^2 L_g + r \tan \theta / 3 \]  

The time dependence and the effective grain level can be modelled as

\[ e(t) = \begin{cases} \left( \frac{3At}{\pi \rho \tan \theta} \right)^{1/3} & t \leq \frac{r^3 \pi \rho \tan \theta}{3A} \\ r & t \geq \frac{r^3 \pi \rho \tan \theta}{3A} \end{cases} \]  

and

\[ L_e(t) = \begin{cases} L_g(t) + \frac{r_e \tan \theta}{3} & r_p = 0 \leq \frac{r^3 \pi \rho \tan \theta}{3A} \\
L_g(t) + \frac{r \tan \theta}{3} - \frac{r_p}{3r^2} (\tan \theta + \tan \beta) & r_p \leq r \\
L_g(t) - \frac{r_e \tan \theta}{3} - \frac{A_p}{\pi r^2 \rho} (t - T) & r_p \leq r \end{cases} \]
applying the extreme value calculation method, we get

\[
p_a = \frac{\kappa \gamma (\sin(\varphi + \theta) \cos \varphi \omega + \sin(\varphi + \theta) (2z - R \cot \theta + R \tan \beta))}{2 \sin(\varphi \omega + \varphi + \theta)} + \frac{\gamma R (\sin(\varphi + \theta) \cos \varphi \omega)}{2 \sin(\varphi \omega + \varphi + \theta)} \tag{6}
\]

The final solution is

\[
\psi = \sum \left\{ \left[ a_n(z) + A_n \right] \ast \psi_n^{(\alpha)} + \left[ b_n(z) + B_n \right] \ast \psi_n^{(\beta)} \right\} \tag{7}
\]

4. Numerical example

Figure 1. Displacement \( v \).

Figure 2. Shear stress \( \tau \).
Fig. 1 and Fig. 2 show the change of axial displacement and normal stress with time. It can be seen from the figure that the displacement and stress increase rapidly or decrease to a limit position with the increase of time, which shows that the non-zero eigenvalue solution only has an obvious effect near the end, which is consistent with the explanation of Saint Venant's principle.

Acknowledgments
This research was financially supported by Major Natural Science Research Projects in Colleges and Universities of Jiangsu Province (17KJA430012).

References
[1] Makkonen, L. (1998) Modeling power line icing in freezing precipitation. Atmos. Res., 1998, 46: 131-142.
[2] Barbara, J.M, Leo, L. (1999) Muddy waters: temporal variation in sediment discharging from a karst spring. J. Hydrol. 214: 165-178.
[3] Alan, A.S. (1999) Integrating simulation and design for stormwater management. Water Sci. Technol., 39: 261-268.
[4] Rossikhin, Y.A., Shitikova, M.V. (2001) New method for solving dynamic problems of fractional derivative viscoelasticity. Int. J. Eng. Sci., 39: 149-176.
[5] Pipkin, A.C., Rogerst, G.A. (1968) Nonlinear integral representation for viscoelastic theories. J. Mech. Phy. Solid., 16: 59-72.
[6] Suarez, L,E, Shokooh, A., Arroyo, J. (1997) Finite element analysis of beams with constrained damping treatment modeled via fractional derivatives. Appl. Mech. Rev., 50: 416-454.
[7] Jin, T.L., Ha, N.S., Goo, N.S. (2014) A study of the thermal buckling behavior of a circular aluminum plate using the digital image correlation technique and finite element analysis. Thin Wall. Struct., 77: 187-197.