AIRPORTS AND THEIR INFRASTRUCTURE

UDC 624.042
DOI: 10.18372/2306-1472.1.13655

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STOCHASTIC CALCULATON OF THE WALL OF STEEL VERTICAL SILOS

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Abstract

In the article the practical questions of probabilistic calculation of sheets of the case of vertical steel tanks for storage of grain are solved. The search for the reliability function is based on the general author's technique, which is to find the characteristics of the random variable of the critical factor. In this case, the random maximum values of the horizontal pressure of the bulk material are presented in two forms - taking into account the correlation connection of its components (specific gravity, internal friction angle, ratio of lateral pressure and ratio of friction on the wall) and for the case of completely independent variables. Possible ways to simplify the Jansen-Kenen reference curve for horizontal pressure and to replace it with bilinear dependence are considered. In this case, two ways for obtaining approximating curves are presented. The tangential method is based on the construction of tangent points at the top and bottom of storage volume. For an alternative method, the construction of the ducts from these points to the midpoint of the capacity is performed .Graphical comparisons and analysis of these methods with the following argumentation of their application are presented .It is shown that the method of tangents greatly overestimates the value of horizontal pressure at the height of the capacity and leads to the greatest error in the region of the central part, on the other hand the sieve method approximates the curve more correctly.

Keywords: silo; reliability; stochastic processes; particulate solids properties; coefficient of variation; coefficient of critical factor

1. Introduction

Sheets of the storage silos work on tension and are checked for durability from the horizontal pressure of the bulk material. Deterministic calculation of these elements is carried out using the finite element method or analytically. However, it should be noted that the calculation, which is based on probabilistic principles, is a more logical and relevant approach that contributes to increasing the efficiency of design and increasing its economic feasibility while maintaining the required level of reliability. For the possibility of using it in the context of engineering calculations, it is necessary that the algorithm of the decision is as simple as possible and has an analytical expression.

2. Statement of the problem

The calculation of the reliability of steel storage tanks is a complex multi-stage process. It is expedient to carry out a practical search for the reliability function by using the boundary equation with the use of critical factor. The stochastic nature of the estimated values of this equation calls for the use of methods of probability theory and mathematical statistics. Therefore, for the possibility of formulating the engineering methodology for calculating reliability, it is necessary to introduce a number of simplifications that will allow simultaneously to obtain the solution of the problem and will not significantly affect the accuracy of the calculation. One such possible approach is the application of approximated dependencies for a number of functional expressions. In particular, in the expression of the horizontal pressure of loose material represented by the Jansen-Kenen formula.

3. Analysis of the latest research

The presented paper is a continuation of the global study of the reliability of steel silos for bulk products performed by the author .The work is based on the methods of the theory of probabilities, which in the practice of engineering design are widely covered in scientific sources [1-5]. Also note the scientific work of recent years concerning this type of deterministic calculation for this kind of structures [6-10] and behavior of bulk materials [11].

4. Forming the aims of the article

In this work, the authors searched for an approximated dependence to represent the Jansen-Kenen reference curve to determine the horizontal pressure of bulk material. Using this expression will greatly simplify the definition of the random value of the critical factor of the sheets of the steel in vertical silo case and, accordingly, facilitate the general procedure for the probabilistic calculation of these elements.

5. General method of solution of the problem

The solution of the tasks of reliability of building structures is a complex multi-stage process, which requires taking into account a large number of factors, including the random nature of external loads and influences, the complexity of analytical and computational nature, etc. In relation to sheets of steel silos, it is necessary to take into account the probabilistic nature of the horizontal pressure, which is subject to the statistical distribution of characteristics of bulk material in laboratory studies. In addition, the final solution should have an analytically simple look, so that it can be applied in practical tasks. For the possibility of probabilistic calculations we will apply the coefficient of the critical factor $\tilde{K}$, which is characterized by the ratio of the generalized value of the effort $\tilde{S}$ to generalized strength $\tilde{R}$

$$\tilde{K}_R = \tilde{S} / \tilde{R} \le 1.0 \,, \qquad (1)$$

We will use the situation, according to which any random variable can be expressed through normalized random variables with zero mathematical expectations and mean square deviations equal to one. For a random variable of a critical factor, there will be a fair relation

$$\tilde{K}_R(\tilde{\gamma}_S, \tilde{\gamma}_R) = \frac{m_S \cdot (1+\tilde{\gamma}_S V_S)}{m_R \cdot (1+\tilde{\gamma}_R V_R)} = \frac{V_R}{V_S} p_S \frac{1+\tilde{\gamma}_S V_S}{1+\tilde{\gamma}_R V_R}, \qquad (2)$$

where $\tilde{\gamma}_R$ and $\tilde{\gamma}_S$ –normalized values of generalized strength and generalized effort; p_S − correlation of the standards of generalized effort and strength σ_S, σ_R V_S and V_R − their coefficients of variation

$$V_S = \sigma_S / m_S, \quad V_R = \sigma_R / m_R, \quad p_S = \sigma_S / \sigma_R, \qquad (3)$$

The main type of loading for sheets of silos container body is the horizontal pressure of the bulk material. Its probabilistic nature is due to the statistical spread of a number of characteristics - specific weight $\tilde{\gamma}_g$, the angle of internal friction $\tilde{\varphi}_g$, the coefficient of lateral pressure $\tilde{\lambda}_g$ and the coefficient of friction on the wall $\tilde{\mu}_g$. These characteristics can be taken correlated or completely independent.

In general, the horizontal pressure of the bulk material $p_h(z)$ walls of the shell of round silage in diameter D_w at the level z from the top of the cylindrical portion is given by Jansen-Kenen formula [12]

$$p_h(z) = \frac{\gamma_g D_w}{\mu_g 4}\left(1-\exp\left(-\frac{4z}{D_w}\mu_g\lambda_g\right)\right). \qquad (4)$$

In the probabilistic approach we can represent formula (4) in two forms - taking into account the correlation of its constituents and for the case of completely independent variables

$$p_h(z) = \frac{m_g}{m_\mu}\cdot\frac{(1+\gamma_G V_g)}{(1+\gamma_G V_\mu)}\cdot\frac{D_w}{4}\times \\ \times\left\{1-\exp\left[-\frac{4z}{D_w}\cdot m_\mu \cdot m_\lambda \cdot (1+\gamma_G V_\mu)\cdot(1+\gamma_G V_\lambda)\right]\right\}, \qquad (5)$$

$$p_h(z) = \frac{m_g}{m_\mu}\cdot\frac{(1+\gamma_g V_g)}{(1+\gamma_\mu V_\mu)}\cdot\frac{D_w}{4}\times \\ \times\left\{1-\exp\left[-\frac{4z}{D_w}\cdot m_\mu \cdot m_\lambda \cdot (1+\gamma_\mu V_\mu)\cdot(1+\gamma_\lambda V_\lambda)\right]\right\}. \qquad (6)$$

where m_g, m_λ and m_μ − mathematical expectations of random values of specific weight $\tilde{\gamma}_g$, the lateral pressure factor $\tilde{\lambda}_g$ and the coefficient of friction on the wall $\tilde{\mu}_g$; V_g, V_λ and V_μ their coefficients of variation; γ_G − is a normalized random variable with a normal distribution law.

For an occasional magnitude of the critical factor of the sheets of steel storage capacity, the expression will be correct

$$\tilde{K}_R = \frac{1}{2}\cdot\frac{\tilde{p}_h}{\tilde{R}}\cdot\frac{D_w}{t_w}\cdot\frac{1}{\gamma_{neto}}. \qquad (7)$$

where D_w and t_w – the diameter and thickness of the sheets of the body (the thickness of the sheets in height is variable); γ_{neto} – the coefficient of weakening of the section through the bores openings.

Taking into account (4), and representation $\tilde{R}=m_R\left(1+\tilde{\gamma}_R V_R\right)$ formula (7) takes the form (for the case of a correlation connection)

$$\tilde{K}_R=\frac{1}{\gamma_{neto}}\cdot\frac{1}{m_R}\cdot\frac{m_g}{m_\mu}\cdot\frac{(1+\tilde{\gamma}_G V_g)}{(1+\tilde{\gamma}_G V_\mu)(1+\tilde{\gamma}_R V_R)}\cdot\frac{D_w^2}{8t_w}\times$$
$$\times\left\{1-\exp\left[-\frac{4z}{D_w}\cdot m_\mu\cdot m_\lambda\cdot(1+\tilde{\gamma}_G V_\mu)\cdot(1+\tilde{\gamma}_G V_\lambda)\right]\right\}, \qquad (8)$$

Formulas (4), (5) and (7) have a complicated mathematical structure in which the desired function is nonlinearly related to its arguments. Using such expressions when performing probabilistic calculations is rather uncomfortable, so the question is about simplifying procedures.

In the first place, you can use the replacement of the standard Jansen-Kenen curve for horizontal pressure. To do this, we apply bilinear dependence. Approximating straight lines can be constructed in two ways. First, the initial curve may be replaced by two tangents, which hold at the top points ($z=0$)and bottom ($z=H_w$) of storage capacity. In the second case, we can build two secants from these points($z=0$ i $z=H_w$) to the point $z=H_w/2$. For the first approach we apply the name of the method of tangential, and for the second - the Secant method.

In fig. 1 shows a graphical interpretation of both methods. At the same time, it is possible to notice that the first of them greatly overestimates the value of horizontal pressure in the height of the container and leads to the greatest error in the central part of the area.

The cutting method approximates the curve (4) more correctly, but somewhat underestimates the value. Taking into account that the Jansen-Kenen formula is the result of averaging a large number of experiments on loose materials, the proposed approximation may be considered acceptable. In addition, it allows you to significantly reduce the time when calculating loads in software products of finite element analysis (SCAD, Lira).

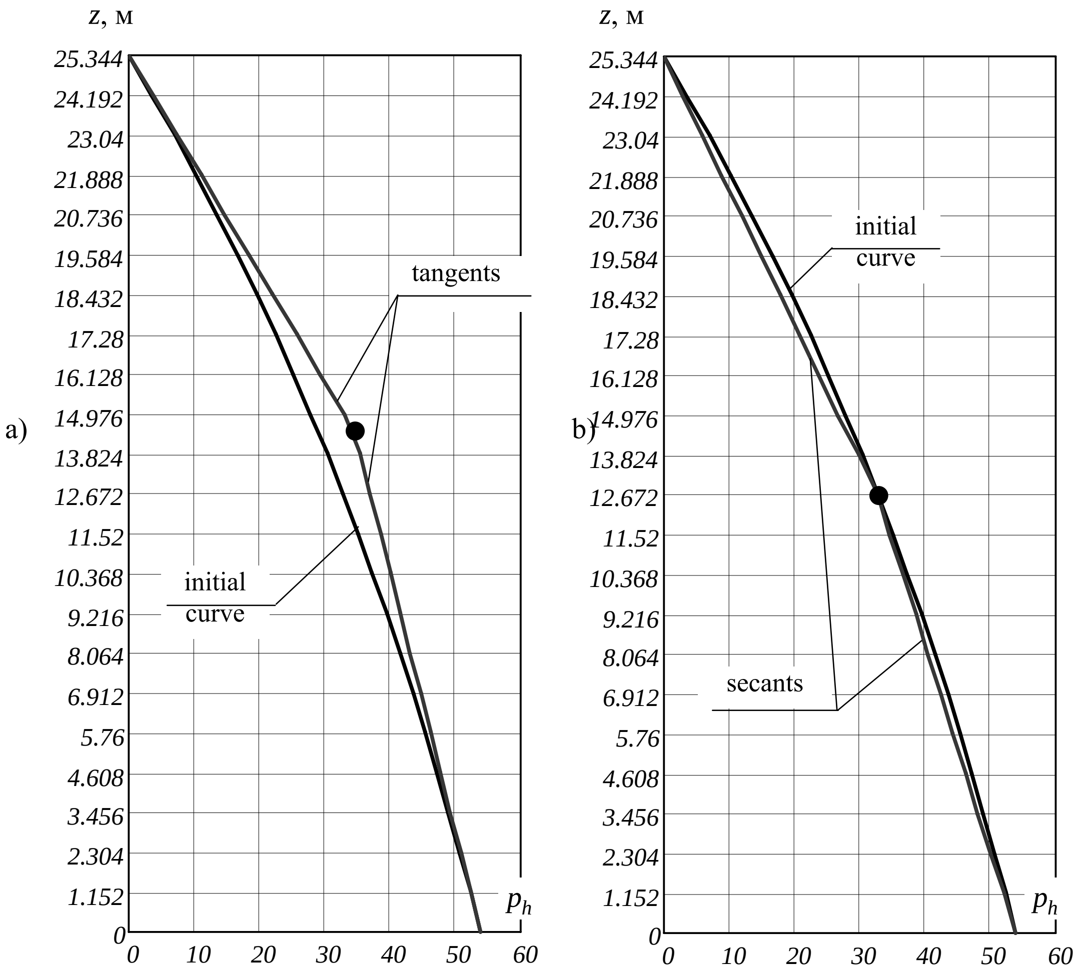

Fig. 1. To the approximation of the Jansen-Kenen formula: a − is a method of tangent; b − is the Secant method

The bilinear analogue of the Jansen-Kenen formula will look like this

$$p_h(z) = \begin{vmatrix} p_{h,m} \cdot z / z_H & if \quad 0 \le z \le z_H; \\ p_{h,m} + \Delta p_h \cdot (z - z_H)/(H_w - z_H) & if \quad z_H < z \le H_w, \end{vmatrix} \quad (9)$$

where is the height z_H change the angle of inclination of the straight lines for the cutoff method $z_H = H_s/2$, and for the tangential method it is determined by the formula

$$z_H = H_w \xi_g = H_w \left[\eta_g - \frac{\exp(-0.5\eta_g)}{2\mathrm{sh}(0.5\eta_g)} \right], \quad (10)$$

where $\eta_g = H_w \lambda_0 f_g / \rho_s$ − dimensionless storage capacity parameter; ρ_s − hydraulic radius.

Given the fact that the hydraulic radius ρ_s for round capacities equals $D_w/4$, we get a new record for the coefficient η_g

$$\eta_g = 4\Delta_w \lambda_0 f_g, \quad (11)$$

where $\Delta_w = \frac{H_w}{D_w}$.

At the altitude z_H and $z = H_w$, which corresponds to the bottom of the capacity will be the value of the pressure will be determined by the formula

$$p_{h,m} = \gamma_g \rho_s \frac{1 - \exp(-\omega_g \eta_g)}{f_g} \quad (12)$$

$$p_{h,\max} = \gamma_g \rho_s \frac{1 - \exp(-\eta_g)}{f_g} \quad (13)$$

$$\Delta p_h = p_{h,\max} - p_{h,m} = \gamma_g \rho_s \frac{\exp(-\eta_g) - \exp(-\omega_g \eta_g)}{f_g} \quad (14)$$

where $\omega_g = \xi_g$ − for the tangential method and $\omega_g = 0.5$ − for the secant method.

Since the application of the method is more arguable, we will express the formula (9) in a simpler form, applying dimensionless height $y = z / H_w$

$$p_h(y) = \begin{vmatrix} 2 p_{h,m} y & if \quad 0 \le y \le 0.5; \\ p_{h,m}\left[1 - \Delta_g (2y - 1)\right] & if \quad 0.5 < y \le 1, \end{vmatrix} \quad (15)$$

where Δ_g − a parameter that can be calculated by the formulas given below

$$\Delta_g = \frac{1 - \exp(-0,5\eta_g)}{1 - \exp(-\eta_g)}. \quad (16)$$

$$\Delta_g \approx 0,5 + 0,125\eta_g = 0,5 \cdot \left(1 + \Delta_w \lambda_0 f_g\right). \quad (17)$$

Note that formula (16) allows to obtain exact solution, and (17) allows approximated one. Formula (17) is tangent to the desired function at the point $\eta_g = 0$ and an acceptable result in accordance with it can be obtained at values $\eta_g < 2$.

Further simplification of probabilistic calculations is based on the construction of a probabilistic model of the value of horizontal pressure $p_{h,m}$ with averaged characteristics of the coefficient and the use of expression for critical factor of the sheets on a critical probability scale

$$\tilde{K}_R = \frac{A_K y^2 + B_K y + C_K}{t_w} \quad (18)$$

where coefficients A_K, B_K and C_K are determined by the least squares method for a particular type of storage product, storage geometry and steel class. Relevant procedures for the justification of this expression are indicated in previous author's studies.

Probabilistic characteristics of pressure $p_{h,m}$ are calculated using the simulation procedure and are standardized for different storage products.

6. Conclusions of this study and prospects for further development in this provision.

1. The stated approach to solving the problem of reliability of elements of steel storage tanks is formulated by determining the characteristics of random variable of coefficient of critical factor.
2. We have described the expression of horizontal pressure of bulk material of the wall of shell of a round silo in diameter in the probabilistic version, taking into account the correlation connection of its components and for the case of completely independent variables.
3. The proposed representation of the Jansen-Kenen reference curve for horizontal pressure by bilinear dependence of two methods with the subsequent graphic validation of the results is proposed.
4. A simple formula dependence is obtained for the approximated expression of Jansen-Kenen formula in the exact and approximate form, which can be used for probabilistic calculations of wall of the body of vertical steel storage silos.

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Імовірнісний розрахунок стінки металевих вертикальних силосів

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Вирішуються практичні питання імовірнісного розрахунку листів корпусу вертикальних сталевих ємностей для зберігання зерна. Пошук функції надійності базується на загальній авторській методиці, що полягає у пошуку характеристик випадкової величини критичного фактору. При цьому випадкові величини максимумів горизонтального тиску сипкого матеріалу представлені у двох виглядах - з урахуванням кореляційного зв’язку його складових (питомої ваги, кута внутрішнього тертя, коефіцієнту бокового тиску та коефіцієнту тертя об стінку) і для випадку повністю незалежних величин. Розглядаються можливі шляхи спрощення еталонної кривої Янсена-Кенена для горизонтального тиску та заміною її на білінійну залежність. При цьому представлені два шляхи отримання апроксимуючих кривих. Метод дотичних базується на побудові дотичних в точках верху та низу ємності зберігання. Для альтернативного методу виконується побудува січних з цих точок до точки середини ємності. Наводиться графічне порівняння та аналіз даних методів із наступною аргументацією їх застосування. Показано, що метод дотичних набагато завищує значення горизонтального тиску за висотою ємності та призводить до найбільшої похибки в районі центральної частини, а метод січних апроксимує криву більш коректно. Отримана проста формульна залежність для апроксимованого виразу формули Янсена-Кенена в точному та наближеному вигляді, яка може бути застосоване для здійснення імовірнісних розрахунків стінки корпусу вертикальних сталевих ємностей зберігання.

Ключові слова: силос; надійність; випадковий процес; коефіцієнт критичного фактору; крива Янсена-Кенена

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Решаются практические вопросы вероятностного расчета листов корпуса вертикальных стальных емкостей для хранения зерна. Поиск функции надежности базируется на общей авторской методике, которая заключается в поиске характеристик случайной величины критического фактора. При этом случайные величины максимумов горизонтального давления сыпучего материала представлены в двух видах - с учетом корреляционной связи его составляющих (удельного веса, угла внутреннего трения, коэффициента бокового давления и коэффициента трения о стенку) и для случая полностью независимых величин. Рассматриваются возможные пути упрощения эталонной кривой Янсена-Кенена для горизонтального давления и заменой ее на билинейную зависимость. При этом представлены два пути получения аппроксимирующих кривых. Метод касательных базируется на построении касательных в точках верха и низа емкости хранения. Для альтернативного метода выполняется построение секущих из этих точек к высотной отметке середины емкости. Приводится графическое сравнение и анализ данных методов с последующей аргументацией их применения. Показано, что метод касательных сильно завышает значение горизонтального давления по высоте емкости и приводит к наибольшей погрешности в районе центральной части, а метод секущих аппроксимирует кривую более корректно. Полученна простая формульная зависимость для аппроксимированного выражения формулы Янсена-Кенена в точном и приближенном виде, которая может быть использована для осуществления вероятностных расчетов стенки корпуса вертикальных емкостей хранения.

Ключевые слова: силос; надежность; случайный процесс; коэффициент критического фактора; кривая Янсена-Кенена

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