

Regression Analysis and Optimization of Experimental Data on The Cleaning Efficiency of The Peg Screw

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Abstract

The article uses regression analysis to process the results of experimental studies conducted on three parameters that determine the maximum cleaning efficiency of a peg-type screw cleaner: the peg placement pitch s , the mesh hole width b , and the screw rotation speed n . Based on the B3 second-order Boh plan, 14 experiments were conducted, and the results were summarized in the form of a complete quadratic regression equation. All ten coefficients of the equation turned out to be statistically significant ($t > 2.048$), and the coefficient of determination was $R^2 = 0.964$. As a result of the canonical analysis of the response surface, it was found that the stationary point of the model is the saddle point (minimax); the most optimal combination of parameters within the studied region is $s \approx 216$ mm, $b \approx 6.9$ mm, $n = 130$ rpm, where $\eta_0 \approx 84.2\%$ is achieved according to the model. It is shown that the results obtained are in good agreement with the parameters of the experimental sample ($b = 6$ mm, $n = 160$ rpm) adopted on the basis of the theoretical model.

Keywords: Regression analysis, Box plan, response surface, canonical analysis, optimization, cleaning efficiency, Fisher's criterion.

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1. Introduction

The previously developed theoretical model [1] indicates three parameters that most significantly determine the cleaning efficiency of the peg screw: the peg placement

pitch s , the size of the perforated mesh holes b , and the working tool rotation speed n . To verify this theoretical dependence in practice and obtain a working formula suitable for use directly in engineering calculations, a three-factor experiment was conducted based on the

second-order Boh plan B3 [1, 4]. Plan B3 is cost-effective in terms of the number of experiments: only 14 different level combinations are required for the three factors, instead of the 27 combinations required in a full three-level factor experiment. At the same time, this plan allows for the construction of a complete quadratic regression equation, taking into account the interaction of factors in pairs.

Such an experimental-statistical approach is of complementary importance for the analytical-theoretical description of the cleaning process. While the theoretical model [1] describes the physical mechanism of the process-through geometric coverage, impact intensity, pile-slit compatibility, and hole-pass probability-regression analysis yields a quantitative dependence that accounts for the combined, including interactive, effects of factors under real experimental conditions. The combined application of two approaches - understanding the mechanism of the process through a theoretical model and linking it to specific numerical parameters

through a regression model - forms a reliable scientific basis for the design and optimization of a peg screw.

The purpose of the article is to construct a complete quadratic regression equation linking cleaning efficiency with factors s , b , and n based on experimental results, verify the statistical significance of its coefficients and model adequacy, determine the optimal operating mode within the studied region through canonical analysis of response surfaces, and compare the obtained results with the theoretical model developed in work [1].

2. Methodology

2.1. Experimental plan and factor levels

The following factors were taken as variables: X1 - pile installation pitch in the screw s , mm; X2 is the width of the waste screen hole b , mm (the hole length is set at 50 mm); X3 - screw rotation speed n , rpm. The levels of variation determined based on the design range of the cleaner under consideration are presented in Table 1.

Factor	Name	Unit of measurement	Sub-level (-1)	Primary level (0)	High level (+1)	Step of variation
X1	Pile installation step s	mm	200	250	300	50
X2	The width of the mesh hole b	mm	4.	6.	8.	2.
X3	Rotation frequency n	rpm	130	150	170	20

2.2. Measurement results

According to Plan B3, each of the 14 experiments (8 points of the full-factor experiment and 6 "star-shaped" points where only one factor is changed, while the other

two factors are recorded at the main level) were repeated three times to assess the reproducibility of the measurement results. The planning matrix, the results of three parallel experiments, and their average values are presented in Table 2.

№	X1	X2	X3	Y1	Y2	Y3	S2	Yx
1.	-1;	-1;	-1;	74.4	74.7	74.6	0.023	74.57
2.	+1	-1;	-1;	71.6	71.5	71.4	0.010	71.50
3.	-1;	+1	-1;	82.0	82.3	82.1	0.023	82.13
4.	+1	+1	-1;	77.4	77.6	77.6	0.013	77.53
5.	-1;	-1;	+1	74.8	74.9	74.7	0.010	74.80
6.	+1	-1;	+1	73.7	73.6	73.4	0.023	73.57
7.	-1;	+1	+1	78.6	78.4	78.5	0.010	78.50

8.	+1	+1	+1	75.0	75.3	75.1	0.023	75.13
9.	-1;	0	0	83.3	83.2	83.5	0.023	83.33
10	+1	0	0	76.5	76.2	76.4	0.023	76.37
11.	0	-1;	0	74.2	74.6	74.3	0.043	74.37
12	0	+1	0	80.3	80.4	80.3	0.003	80.33
13	0	0	-1;	82.8	83.0	82.9	0.010	82.90
14	0	0	+1	81.2	81.4	81.3	0.010	81.30

2.3. Testing the homogeneity of variances - Cochran's criterion

Before constructing the regression model, the Cochran criterion was applied to ensure that the spread of parallel measurements did not exceed the margin of random error in each of the 14 experiments:

$$G_p = S_{2\max}/\Sigma S_{2j} = 0.0433/0.250 = 0.173;$$

At a significance level of 0.05, when the number of degrees of freedom in the subgroup is $fl = m - 1 = 2$ and the number of groups is $k = 14$, the table value of the criterion is $G_{kr} = 0.296$. Since the calculated value $G_p = 0.173$ is less than the value in the table, the repeated variances in all 14 experiments are homogeneous and can be averaged: $S_{2\{y\}} = (1/14) \Sigma S_{2j} = 0.0179$, where the number of degrees of freedom $fx = 14 \cdot (3 - 1) = 28$. A small value of this variance (the variance in parallel measurements of cleaning efficiency does not exceed $\pm 0.2\%$) indicates good repeatability of the experiment.

2.4. Method for estimating regression coefficients

Based on the results of 14 experiments, the coefficients of the complete quadratic regression equation were determined, representing the relationship between factors X_1 , X_2 , X_3 and cleaning efficiency η_0 in the encoded form using the least squares method:

$$Y = b_0 + b_{1X_1} + b_{2X_2} + b_{3X_3} + b_{12X_1X_2} + b_{13X_1X_3} + b_{23X_2X_3} + b_{11X_{12}} + b_{22X_{22}} + b_{33X_{32}} \quad (22).$$

The significance level of each coefficient was estimated using Student's t-test using the recurrence variance $S_{2\{y\}}$: $t_i = |b_i|/\sqrt{(S_{2\{y\}} \cdot C_{ii})}$, where C_{ii} is the diagonal element of the inverse $(XTX)^{-1}$ matrix. Table values $t_{kr}(0.05; 28) = 2.048$.

3. Results

3.1. Regression coefficients and their significance

Indicator	Value	Standard error	t-test	Significance
b_0 (free term)	81,667	0.085	958.8	significant
b_1 (X_1 , step c)	-1.923	0.042	-45.5;	significant
b_2 (X_2 , hole b)	+2.483	0.042	58.8	significant
b_3 (X_3 , rotation n)	-0.533	0.042	-12.6	significant
b_{12} (X_1X_2)	-0.458	0.047	-9.7	significant
b_{13} (X_1X_3)	+0.383	0.047	8.1	significant
b_{23} (X_2X_3)	-1.042	0.047	-22.0	significant
b_{11} (X_{12})	-1.817	0.085	-21.3;	significant
b_{22} (X_{22})	-4.317	0.085	-50.7;	significant

b33 (X32)	+0.433	0.085	5.1	significant
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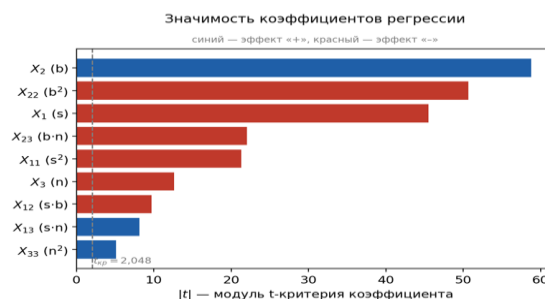


Figure 1. Pareto diagram of the significance of regression coefficients ($|t|$ is the modulus value of the t-test). The mesh size has the greatest impact on cleaning efficiency-both in linear (X2) and quadratic (X22) terms.

As seen from the table, all ten coefficients turned out to be statistically significant - no term of the equation can be excluded without losing the accuracy of the description. This means that the dependence of cleaning efficiency on the pile pitch, hole size, and rotation frequency is significantly nonlinear, and there are clear interactions between all three factors.

3.2. Regression equation

Substituting the determined coefficients into the equation, we obtain the regression equation for the coded variables:

$$Y = 81.667 - 1.923X_1 + 2.483X_2 - 0.533X_3 - 0.458X_1X_2 + 0.383X_1X_3 - 1.042X_2X_3 - 1.817X_{12} - 4.317X_{22} + 0.433X_{32} \quad (23).$$

By performing an inverse transition from coded variables to natural ones using the formulas $X_1 = (s - 250) / 50$, $X_2 = (b - 6) / 2$, $X_3 = (n - 150) / 20$, we obtain a working

formula that can be applied directly in engineering evaluation for any combination of s (mm), b (mm), and n (rpm) within the studied range:

$$\eta_0 = 12.00 + 0.295s - 0.000727s^2 - 0.291n + 0.00108n^2 + 19.24b - 1.079b^2 + 0.000383sn - 0.00458sb - 0.0260bn \quad (24)$$

3.3. Model accuracy and adequacy

The coefficient of determination of the constructed model is $R^2 = 0.964$, i.e., equation (23) explains 96.4% of the cleaning efficiency distribution between the 14 experiments, while the share of unexplained (residual) variability accounts for less than 4%. Formal verification according to the Fisher criterion yields a less positive result: the mean of the squares of inadequacy is $MS_{lof} = 1.733$ ($f_{lof} = N - p = 14 - 10 = 4$), from which $F_{his} = MS_{lof} / S_2\{y\} = 1.733 / 0.0179 \approx 97$, which is $F_{kr}(0.05; 4; 28)$ is several times greater than ≈ 2.71 .

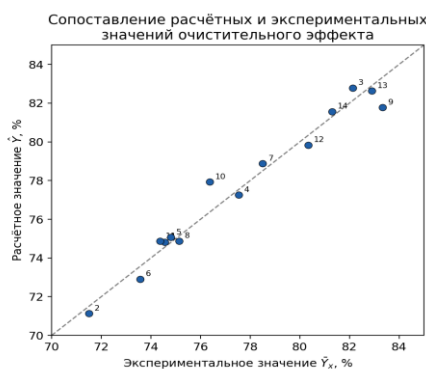


Figure 2. Comparison of the calculated and experimental cleaning efficiency values. The dot numbers match the experiment numbers.

Practically, the reason for such a result is evident from the scattering diagram of the calculated and experimental values (Fig. 2): almost all points are located with a deviation to the bisector line within 0.3–0.7%, while only two points-experiments 9 and 10 (in which only the stake pitch s was changed while maintaining b and n at the primary level) -deviate from the model by 1.56% in opposite directions. It is possible that there is a weak cubic component here, which Plan B3 does not provide for sufficient degrees of freedom to reliably highlight. Since the variance of repeatability is very small ($\pm 0.2\%$), the Fisher criterion also detects this small and local difference; nevertheless, the equation correctly explains

96% of the response variability, and the qualitatively general picture of factor influence is not in doubt; therefore, models (23) – (24) were adopted for further analysis of the response surface.

3.4. Analysis of response surfaces

To provide a visual representation, equation (23) was constructed in the form of three response surfaces - where one of the factors was recorded alternately at the main level, and the dependence of cleaning efficiency on the other two factors was considered (Figures 3-5).

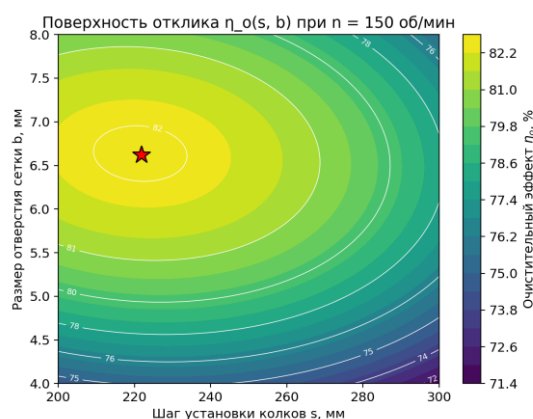


Figure 3. Answer surface $\eta_o(s, b)$ at rotation speed $n = 150$ rpm. The maximum value in the section is marked with an asterisk

The section by "step-hole size" factors (Figure 3) has a clearly expressed dome-shaped appearance in the area under study, with the maximum value located around $s \approx$

220–230 mm and $b \approx 6.5$ –6.7 mm-this is typical for a well-planned experiment covering the optimal region.

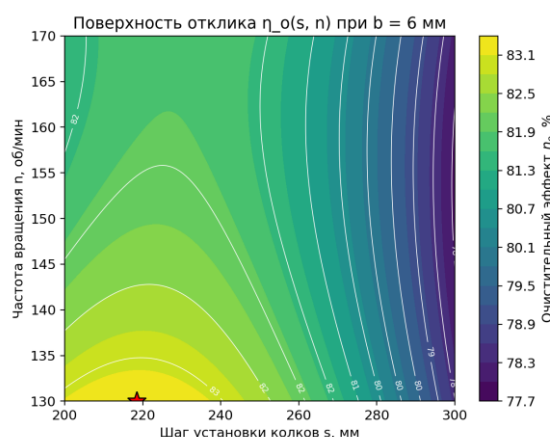


Figure 4. Answer surface $\eta_o(s, n)$ with mesh hole size $b = 6$ mm. The maximum in the cross-section is located at the lower boundary of the studied range in terms of rotational speed.

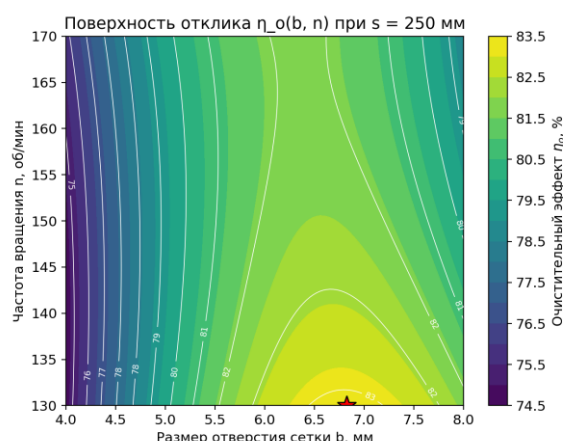


Figure 5. Answer surface $\eta_o(b, n)$ at pile pitch $s = 250$ mm. The maximum is also shifted toward the lower boundary of the studied range in terms of rotational speed.

Sections containing rotation frequency n (Figs. 4 and 5) have a different characteristic: equal-level lines do not close within the region, forming a dome; instead, the maximum cleaning efficiency "sticks" to the lower limit of the studied range - $n = 130$ rpm.

3.5. Canonical Analysis and Optimal Operating Mode

In the formal canonical analysis of the surface of equation (23), as a result of solving the system of equations $\partial Y / \partial X_i = 0$, a stationary point is obtained in the form $X_1 = -0.444$, $X_2 = 0.186$, $X_3 = 1.035$ (in natural variables $s \approx 228$ mm, $b \approx 6.4$ mm, $n \approx 171$ rpm). However, the eigenvalues of the matrix of the quadratic form at this point are -4.39 ; -1.82 and $+0.51$, i.e., they have different signs-the stationary point is not a maximum, but a saddle point (minimax): in some directions, the surface bends upward at this point, and in other directions, it bends downward. This means that the true best result within the studied domain should be sought at the boundary of the experimental domain, rather than at a stationary point.

Direct sorting by a grid of values within the cube $-1 \leq X_i \leq +1$ shows that the maximum calculated cleaning efficiency value $\eta_o \approx 84.2\%$ is achieved at values of $s \approx 216$ mm, $b \approx 6.9$ mm, and $n = 130$ rpm, i.e., at the lower bound of the studied rotation speed range. Since the optimal value is not strictly contained within the plan, but is "attached" to its boundary, it cannot be ruled out that at lower rotation speeds (less than 130 rpm) the cleaning efficiency may continue to increase; to provide a final answer to this question, it is necessary to conduct a series of additional experiments outside the studied range. Out of the 14 experiments conducted in practice, the best

result was shown by experiment 9 ($s = 200$ mm, $b = 6$ mm, $n = 150$ rpm), where the cleaning efficiency was $Y_x = 83.33\%$ - this result is well consistent with the model forecast and confirms the correctness of the direction for reducing the pile pitch and using a medium, not excessively high screw rotation speed.

It should also be noted that models (23) – (24) yield correct results only within the range of studied factors ($s = 200$ – 300 mm, $b = 4$ – 8 mm, $n = 130$ – 170 rpm); extrapolation beyond these limits is not recommended, as the behavior of a quadratic polynomial can change rapidly as it moves away from the boundary. Therefore, to determine the true optimum in the region of $n < 130$ rpm, it is recommended to conduct additional research by expanding the experimental range.

4. Conference

The signs and values of the coefficients in equation (22) say a lot about the physical nature of the process. The negative linear coefficient $b_1 = -1.92$ indicates that an increase in the pile installation pitch reduces cleaning efficiency-when the stakes are placed more sparsely, each part of the grid is less exposed to impact. The coefficient $b_2 = +2.48$, which is both positive and significantly larger in magnitude (the largest among all linear terms in terms of significance), confirms that an increase in the mesh size within the studied range of 4–8 mm increases cleaning efficiency. However, the negative quadratic coefficient $b_{22} = -4.32$ indicates that this increase is nonlinear and decreases over time - the dependence on b is domed rather than monotonically increasing.

Rotation frequency n has a weaker effect on cleaning

efficiency than other factors (the smallest of the linear coefficients by modulus value is $b_3 = -0.53$). A negative sign indicates that an increase in rotation speed in the studied range of 130–170 rpm, on the contrary, worsens cleaning rather than improves it. This result does not contradict the theoretical model presented in work [1]: it showed that the probability multiplier $p_1(n)$ reaches saturation at relatively low rotation frequencies, while further increasing the rotation frequency increases the damaging effect of the pegs without increasing the efficiency of waste separation. Consequently, both independent approaches-theoretical and experimental-statistical-come to the same qualitative conclusion regarding the undesirability of rotation frequency in the upper part of the studied range.

It is also useful to compare these experimental conclusions with the parameters of the experimental sample adopted for the theoretical model. According to the results of the theoretical analysis, the mesh hole size $b = 6$ mm and the rotation speed $n = 160$ rpm included in the design fall within the optimal range determined in this regression study (Figures 3-5). That is, the theoretical model and the independently conducted physical experiment show the same range of rational operating modes, which indicates the compatibility and mutual confirmation of both approaches.

From a practical point of view, the obtained formula (24) provides grounds for recommending a two-stage approach in design practice: initially, it is advisable to choose the pile installation pitch s in the range of 200–230 mm, and the mesh hole width b around 6.5–7 mm, then approximate the rotation speed n to the lower part of the studied range (130–150 rpm), taking into account structural and energy constraints. This approach, on the one hand, brings the cleaning efficiency closer to the maximum level, and on the other hand, reduces the risk of fiber damage without unnecessarily increasing the impact intensity of the pegs. At the same time, the fact that the rotation frequency optimum remains within the studied range at $n < 130$ rpm requires additional B3 or central composition experiments-which may serve as a natural continuation of further research.

5. Conclusion

1. Based on the results of the three-factor experiment (plan B3, 14 experiments, three-fold repetition), a complete quadratic regression equation was constructed, expressing the dependence of the cleaning efficiency of the peg screw on the peg installation step, mesh hole size,

and rotation frequency (formulas (22) – (24)). All ten coefficients of the equation were statistically significant ($t > 2.048$), and the coefficient of determination was $R^2 = 0.964$.

2. A formal examination using the Fisher criterion showed that the model is statistically inadequate ($F_{\text{this}} \approx 97 \gg F_{\text{kr}} \approx 2.71$). However, this situation is mainly due to the fact that the variance of repeatability of the experiment is extremely small ($\pm 0.2\%$) and the local deviation at two points of the plan. Overall, the model describes 96% of response variability and qualitatively accurately reflects the influence of all three factors, including their interactions.

3. The largest influence on cleaning efficiency is exerted by the mesh size (the largest linear and quadratic coefficients by modulus value), while the smallest influence is attributed to the rotation frequency of the screw. The influence of each factor is nonlinear, and all three factors have a statistically significant interaction with each other.

4. As a result of the canonical analysis of the response surface, it was found that the stationary point of the model is not a maximum point, but a saddle point. The most optimal combination of parameters within the studied range is $s \approx 216$ mm, $b \approx 6.9$ mm, and $n = 130$ rpm ($\eta_0 \approx 84.2\%$ according to the model). The rotation frequency optimum is located within the studied range, which indicates the expediency of conducting additional experiments at values of $n < 130$ rpm.

5. The parameters adopted for the experimental sample of the cleaner ($b = 6$ mm, $n = 160$ rpm) are located in a range close to the optimal values determined by the independent experimental-statistical method. This confirms the consistency between the theoretical model and the results of the physical experiment.

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