Investigation of the suitable dimensions for hydraulic prop support of self-advancing hydraulic roof support in underground mining at Quang Ninh coal basin in Viet Nam

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Abstract. According to the study, the authors have calculated and determined the reasonable size of hydraulic prop support of self-advancing hydraulic roof support, used in underground coal mining in the Quang Ninh area. The study took into account various factors that are related to the geological conditions of the mine areas, the manufacturing materials, and mining technology. The results obtained from the study can be reasonably applied to calculate the suitable size of the hydraulic prop support based on the durability and stability required for coal mines with similar geological conditions as the Quang Ninh mines. The study was carried out with the aim of improving the efficiency of using hydraulic prop support and reducing product costs. In addition, the research results can be the basis for calculating other types of hydraulic prop support used as a reference for manufacturing other underground coal mining supports at Quang Ninh coal basin.

1. Introduction

Self-advancing hydraulic roof support (Figure 1) is a device used to support coal in a coal mine kiln to protect the mining space and to control kiln pressure.

Figure 1. Self-advancing hydraulic roof support ZH 1600/16/24Z

where: 1 - metal articulated roof beam; 2 - supporting beams; 3 - linear cylinder; 4 - cylinder lift the roof first; 5 - front roof; 6 - rear roof; 7 - hydraulic control station; 8 - shield; 9 - hydraulic prop.
The self-advancing hydraulic roof support must be sustainable, stable, light weighted and long-lasting. The calculation of its design consists of two main parts: the metal articulated roof beam design and the system of hydraulic supports [1, 2].

**Figure 2. Structure of hydraulic prop support**

The principle of operation. The emulsification solution is pumped under high pressure through the main supply line via the distribution valve assembly to the cylinder, causing kinetic energy for the hydraulic prop support operation. The whole structure is movable thanks to the support of bulkhead structure and supporting beams. Firstly, the two-way hydraulic prop support unloads simultaneously leading to a lifting of the hydraulic prop support. The metal articulated roof beam is on the supporting beams, and during the lifting process it injects the solution into the pushing cylinder. The supporting beams represent the fulcrum to support the articulated metal. The roof beam moves forward and loads the pillar to support the wall, completing the support move [3,4].

While working, the maximum total load (Qmax) applied to the roof metal equates to 160 tons (Figure 1). That load is transferred to the ground through 4 hydraulic prop supports. Due to the designated connection between the hydraulic prop supports; the metal roof has a spherical shape which allows it to be "self-selected" during operation. When calculating, hydraulic prop support can be considered as a center bearing bar. Previously, the calculation and testing of the durability of cylinders was accomplished by solving of differential equations combined with stress standard equivalent to Tresca. According to this calculation, the cross-section of the cylinder has not been calculated in the most optimal way. Therefore, it does not properly reflect the ability to withstand the stresses of the cylinder, leading to an increase in the cylinder wall thickness (minimum thickness according to Tresca standards) [5,6]. In this paper, the authors used the equivalent stress standard Von - Mises [7,8] (Figure 3) instead of the Tresca standard and used the criteria for calculating the critical load to calculate the dimensional details on the durability of pistons, cylinders, and pillar stability. This is undertaken in order to minimize the weight of hydraulic prop support, make it easier during construction and reduce the cost of using self-advancing hydraulic roof support.

**Figure 3. Standard stress equivalent Tresca (polygons) and von-Mises (ellipse)**

2. Materials and methods
The piston is a cylindrical bar with a radius rpt in the process of being subjected to axial compressive
force Q and is made of a material with allowable stress as $[\sigma]_1$, so that the smallest radius of the piston is determined by the formula [3,4,5,1]:

$$r_{pr,\text{min}} = \frac{Q}{\pi [\sigma]_1}.$$ (1)

A cylinder is a hollowed geometric shape with an outer radius and an inner radius of $r_2$, $r_1$, the pressure inside the cylinder is $p$, and the problem used to calculate the cylinder is a flat stress problem. For each point on the cylinder, there are 2 main stress components, the stress component $\sigma_t$ is perpendicular to the radius, the stress component $\sigma_\rho$ has a radial direction. To determine the relationship between stress components, we need to solve the differential equation (Lame's equations). The equilibrium differential equation of an element on the cylinder wall (Figure 4) (Lame's equations) is determined as follows [9,10,11,12]:

$$\sigma_t - \sigma_t + r \frac{d\sigma_t}{dr} = 0$$ (2)

After solving equation (2) combined with the initial conditions, we get the law of normal stress and shear stresses in the cylinder as follows:

$$\sigma_i = \frac{pr_i^2 + (r_i^2 r_2^2 / \rho^2) p}{r_2^2 - r_1^2}$$ (3)

$$\sigma_\rho = \frac{pr_i^2 - (r_i^2 r_2^2 / \rho^2) p}{r_2^2 - r_1^2}.$$ (4)

Stress tensor with elements in the cylinder wall is determined:

$$\sigma(\rho) = \begin{bmatrix} \sigma_i(\rho) & 0 & 0 \\ 0 & \sigma_i(\rho) & 0 \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} \frac{pr_i^2 + (r_i^2 r_2^2 / \rho^2) p}{r_2^2 - r_1^2} & 0 & 0 \\ 0 & \frac{pr_i^2 - (r_i^2 r_2^2 / \rho^2) p}{r_2^2 - r_1^2} & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$ (5)

The equivalent stress von - Mises is determined as follows:
Thus, the necessary conditions for a cylinder to work safely are:

$$\sigma_{eq}(\rho) = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} = \rho \frac{r_2^2}{r_2^2 - r_1^2} \sqrt{1 + \frac{3 r_2^4}{\rho^4}}. \quad (5)$$

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$[\sigma_2]$ - reasonable stress of cylinder fabricating material. $\rho$ - distance from the center to the points on the cylinder wall $r_1 \leq \rho \leq r_2$.

Solving equation (6), we get the minimum thickness of the cylinder wall:

$$\Delta s_{\text{min}} = \frac{2 r_i}{-1 + \sqrt{\left(\frac{\sigma_2}{\rho}\right)^2 - 2 + \sqrt{\left(\frac{\sigma_2}{\rho}\right)^2} - 3}}. \quad (7)$$

Minimum thickness according to Tresca standard:

$$\Delta s_{\text{min}} = \frac{2 r_i}{\frac{\sigma_2}{\rho} - 2}.$$

Hydraulic prop support can be considered as two solid cylindrical rods with different parameters of inertia moment and length, piston length is $l_1$, and piston section inertia moment is $I_1$; corresponding cylinder length is $l_2$ and the inertial moment of the piston is $I_2$, axial compression force (Figure 2). The critical load of hydraulic prop support is determined as the solution of the following trigonometric equation [13,14]:

$$K_1 \cos(K_1 l_1) \sin(K_2 l_2) + K_2 \cos(K_2 l_2) \sin(K_1 l_1) = 0 \quad (8)$$

where:

$$k_1 = \frac{Q}{E_1 I_1} \quad ; \quad k_2 = \frac{Q}{E_2 I_2}$$

or:

$$\sqrt{Q_{\text{th}} y_1} \cos\left(\sqrt{Q_{\text{th}} x_1}\right) \sin\left(\sqrt{Q_{\text{th}} x_2}\right) + \sqrt{Q_{\text{th}} y_2} \cos\left(\sqrt{Q_{\text{th}} x_2}\right) \sin\left(\sqrt{Q_{\text{th}} x_1}\right)$$

where:

$$I_1 = \frac{E_1}{4} r_1^4; I_2 = \frac{E_2}{4} (r_2^4 - r_1^4); x_1 = \frac{l_1}{\sqrt{E I_1}}; x_2 = \frac{l_2}{\sqrt{E I_2}}; y_1 = \frac{1}{\sqrt{E I_1}}; y_2 = \frac{1}{\sqrt{E I_2}}$$

E - Young’s modulus of the material. $y_i$ - displacement of hydraulic prop support. Stable condition is given as $P_{\text{th}} < Q_{\text{th}}$ (where $Q_{\text{th}}$ - the critical load at which the hydraulic prop support is stable).

When conducting design calculations for the hydraulic prop supports, conditions which ensure both the strength and their lightest weight are [9,10, 15]:

$$V = \pi \left( r_{11}^2 l_1 - r_{12}^2 l_2 + r_{21}^2 l_1 - r_{22}^2 l_2 \right) \rightarrow \min \quad (10)$$
3. Results and Discussion

According to the study, the calculation of reasonable parameters for hydraulic prop supports is done by combining two conditions: durable condition and stable condition. Combining the conditions (1, 7, 8, 10) we get a reasonable size condition of the hydraulic prop support as follows:

\[
\begin{align*}
    r_{pt,min} &= \sqrt[\pi \sigma^t_1] {\frac{P_t}{\pi \sigma^t_1}} \\
    \Delta s_{min} &= \sqrt[2+\sqrt{\pi \sigma^t_2}] {\frac{2r_1}{2+\sqrt{\pi \sigma^t_2}}} - 1 \Rightarrow \left( r_{pt}, r_1, r_2 \right)_{\text{nl}}. \\
    P_t &\leq Q_{th} \\
    V = \pi \left( r_{pt,1}^2 - r_{1}^2 \right) + r_2^2 l_2 \rightarrow \text{min}
\end{align*}
\] (11)

To satisfy the condition (11), the implementation of the “Brute Force” algorithm on the C programming language is applied. In which:

- The design load of \( P_t \) varies from 25 tons to 40 tons
- The allowed stress of material \( \sigma \) varies from 600 MPa to 750 MPa
- The piston radius varies from 30 mm to 40 mm
- Inside radius of cylinder varies from 55 mm to 65 mm

The method of calculating the reasonable dimensions is shown by the "Brute force" algorithm diagram to find a reasonable size value for hydraulic prop supports as shown below:

| Change the material \( [\sigma] \), loads \( P_t \) | Change the geometric size \( r_{pt}, r_1 \) | Determine the value of \( r_{pt}, r_1 \) to satisfy durable and stable conditions | Find the value of \( V \) so that it is the smallest \( (V_{min}) \) | The sizes \( r_{pt}, r_1 \) are such that the following conditions are met: \( V = V_{min} \) |

Figure 5. Schematic calculation of reasonable dimensions according to the "Brute force" algorithm diagram

After running, the calculation program will receive reasonable results for the size of the hydraulic prop support, corresponding to each load case and material as shown in Table 1.

Table 1 shows:

- reasonable size of \( r_1, r_{pt} \): \( r_1 = 65 \text{ mm}, r_{pt} = 30 \text{ mm} \)
- The dimensions of \( r_2 \) are determined by \( r_1 \) and the inside pressure of the cylinder according to the formula \( r_2 = r_1 + \Delta s_{min} \) \( (\Delta s_{min} \text{ determined by formula 11}) \).

From the obtained results, we draw 3D graphs that show the dependence on dimensions \( r_2 \) on the working load and manufacturing materials of hydraulic prop support (Figure 6), thereby determining the click value. The most reasonable size of hydraulic prop support.

In the case the work face slope is from 00 to 250, the load on hydraulic prop support from 36 tons to 40 tons is determined. The reasonable dimensions of hydraulic prop support are shown in Table 2.
**Table 1.** Dependence of the sphericity coefficient of lead inclusions and average sizes of bronze lead inclusions on the modifier concentration

| Ptk, N | $[\sigma]$, MPa | Qth, Tons | r1, mm | r2, mm | rpit, mm | Vmin, mm$^3$ |
|--------|-----------------|-----------|--------|--------|---------|-------------|
| 250000 | 600  | 42.77301 | 65 | 67.07666 | 30 | 3938887 |
| 250000 | 630  | 42.47301 | 65 | 66.97604 | 30 | 3905003 |
| 250000 | 660  | 42.27301 | 65 | 66.88472 | 30 | 3874297 |
| 250000 | 690  | 42.07301 | 65 | 66.80148 | 30 | 3846345 |
| 250000 | 720  | 41.77300 | 65 | 66.72529 | 30 | 3820788 |
| 250000 | 750  | 41.57300 | 65 | 66.65529 | 30 | 3797334 |
| 280000 | 600  | 43.27301 | 65 | 67.33107 | 30 | 4024784 |
| 280000 | 630  | 43.07301 | 65 | 67.21785 | 30 | 396517 |
| 280000 | 660  | 42.87301 | 65 | 67.11513 | 30 | 3951854 |
| 280000 | 690  | 42.57301 | 65 | 67.02151 | 30 | 3920309 |
| 280000 | 720  | 42.37301 | 65 | 66.93584 | 30 | 3891481 |
| 280000 | 750  | 42.17301 | 65 | 66.85714 | 30 | 3856031 |
| 310000 | 600  | 43.67302 | 65 | 67.58672 | 30 | 4111426 |
| 310000 | 630  | 43.47302 | 65 | 67.46076 | 30 | 4068998 |
| 310000 | 660  | 43.27301 | 65 | 67.34653 | 30 | 4030014 |
| 310000 | 690  | 43.07301 | 65 | 67.24244 | 30 | 3994823 |
| 310000 | 720  | 42.87301 | 65 | 67.1472 | 30 | 3962672 |
| 310000 | 750  | 42.67301 | 65 | 67.05974 | 30 | 3933185 |
| 340000 | 600  | 43.97302 | 65 | 68.43634 | 30 | 4198833 |
| 340000 | 630  | 43.77302 | 65 | 68.70483 | 30 | 4151566 |
| 340000 | 660  | 43.67302 | 65 | 67.58985 | 30 | 4108789 |
| 340000 | 690  | 43.47302 | 65 | 67.46249 | 30 | 4069895 |
| 340000 | 720  | 43.27301 | 65 | 67.35941 | 30 | 4034374 |
| 340000 | 750  | 43.07301 | 65 | 67.26311 | 30 | 4001806 |
| 370000 | 600  | 44.27302 | 65 | 68.10188 | 30 | 4287018 |
| 370000 | 630  | 44.07302 | 65 | 67.95005 | 30 | 4235130 |
| 370000 | 660  | 43.97302 | 65 | 67.81243 | 30 | 4188197 |
| 370000 | 690  | 43.77302 | 65 | 67.6871 | 30 | 4145539 |
| 370000 | 720  | 43.57302 | 65 | 67.57248 | 30 | 4106592 |
| 370000 | 750  | 43.47302 | 65 | 67.46726 | 30 | 4070898 |
| 400000 | 600  | 44.47302 | 65 | 68.36146 | 30 | 4376002 |
| 400000 | 630  | 44.37302 | 65 | 68.19649 | 30 | 4319412 |
| 400000 | 660  | 44.17302 | 65 | 68.04699 | 30 | 4268247 |
| 400000 | 690  | 44.07302 | 65 | 67.91088 | 30 | 4221762 |
| 400000 | 720  | 43.87302 | 65 | 67.78644 | 30 | 4179343 |
| 400000 | 750  | 43.77302 | 65 | 67.67222 | 30 | 4140477 |

**Figure 6.** Dependence of dimension $r_2$ on the load and manufacturing material of hydraulic prop support
Table 2. Dependence of the sphericity coefficient of lead inclusions and average sizes of bronze lead inclusions on the modifier concentration

| $P$, Tons | $[\sigma]$, MPa | $Q$, Tons | $r_1$, mm | $r_2$, mm | $r_{pt}$, mm | $V_{min}$, mm$^3$ |
|-----------|-----------------|----------|-----------|-----------|--------------|----------------|
| 36        | 600             | 44.17302 | 65        | 68.01856 | 30           | 4257535       |
| 37        | 600             | 44.27302 | 65        | 68.10888 | 30           | 4287018       |
| 38        | 600             | 44.27302 | 65        | 68.18286 | 30           | 4316591       |
| 39        | 600             | 44.37302 | 65        | 68.27478 | 30           | 4346252       |
| 40        | 600             | 44.47302 | 65        | 68.36146 | 30           | 4376002       |

4. Conclusion

From applying the equivalent stress standard Von-Mises to Tresca stress and combining with the critical load, it is possible to minimize the cylinder wall thickness, minimize the weight of hydraulic prop support while ensuring its durability and stability. That helps to install, remove and move more smoothly, contributing to reducing product costs. The research results can be referenced to calculate and select some reasonable parameters for self-advancing hydraulic roof support for underground coal mining with different critical loads, made of different materials.

The results of the research can also be used as a reference for the mining design consultancy and mining equipment, for managers to document related teaching in universities, colleges and techniques.

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