Impact of design capacity on optimal parameters of freight aerial mono-cable cableways

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Abstract. Freight aerial cable roads are an efficient mode of transport in mining industry. The purpose of the paper is to develop the method of optimal design of a mono-cable freight ropeway thus reducing the cost of its construction. It is shown that the pitch and height of intermediate supports, the tension force of load-carrying-traction ropes exerts the main influence on the cableway cost. The problem of conditional nonlinear optimization of the mentioned factors ensuring the minimum cost of a cableway at different design capacity up to 600 t/h is formulated and solved. The optimization task is solved taking into account the necessary design, assembly, deformation and strength limitations. Regularities of change of optimal parameters of intermediate supports and load-carrying and traction ropes at the change of design capacity of a cableway were revealed on the basis of analysis of performed calculations. The results of this optimization task allows significantly reducing the cost of construction of freight aerial cableways.

1. Introduction

At present, aerial cableways are considered as a promising mode of transport that solving transport and logistics problems in various sectors of economy [1, 2] and urban environment [3, 4].

Freight cableways have long been used to transport various piece and bulk loads in mining, coal, chemical, metallurgical, energy and agricultural industries. In terms of economy and environment, cable transport is often more profitable than land transport (road, conveyor and rail) [5]. Cable transport is particularly effective when terrain relief (mountain, low-density, difficult-to-travel, remote regions), high density of residential or industrial development and various natural and urban planning restrictions prevent the development of land traffic [1, 6]. For remote high-mountain areas, cable transport can be almost a non-alternative mode of transport for freight and passenger transport [7].

2. Formulation of the research task

The construction of a freight cableway is quite expensive technical and economic task [1, 8]. The total cost of this task includes expenses for survey, design and construction and installation works, purchase of necessary mechanical equipment, creation of the traffic control and surveillance system. The most significant component in the total cost is the costs of manufacturing and installation of intermediate supports along a cableway route and for the purchase of traction and bearing steel ropes [8]. The amount of specified costs directly depends on the number of intermediate supports located along the length of a route, i.e. it depends on the pitch of their installation. As the pitch decreases, the total cost of intermediate supports will increase due to an increase in their number, although the unit cost of the support will decrease due to a decrease in its height. As the pitch increases, the unit support cost and cable cost will increase and cause the total costs to increase, despite the decrease in the number of intermediate supports along the length of a cableway route. The rope tension allows changing the bending deflection. Therefore, the process of changing the height of supports (and their unit cost) can be controlled within certain limits by the targeted tension of the rope. Thus, it is possible to slow down the natural increase in height of intermediate supports by increasing the pitch of their installation. However, this measure will result in additional axial forces in ropes and will require a larger diameter and higher cost rope.
Obviously, the task of arranging intermediate supports along the route of a mono-cable freight ropeway is a task of technical and economic optimization. The purpose of optimization is to provide the minimum costs for intermediate supports and a traction-bearing rope. This optimization task is quite relevant since it allows significantly reducing the cost of construction of a cableway.

3. Mathematical model
The cost of construction of a mono-cable freight ropeway \( C \) consists of the cost of manufacture and assembly of intermediate supports, the cost of construction of a foundation for intermediate supports, the cost of a traction-bearing cable and the cost of technological equipment installed on intermediate supports:

\[
C = n_c C_{f} C_{C} C_{f} l_k ,
\]

(1)

where \( C_{f} , C_{C} , C_{f} \) – unit cost of intermediate support, foundation and technological equipment; \( C_{f} \) – cost of 1 linear meter of a traction-bearing cable; \( n_c = L_r / L_s - 1 \) – number of intermediate supports; \( L_r \) – length of cableway route; \( L_s \) – step of installation of intermediate supports; \( l_k \) – length of a cable between adjacent intermediate supports taking into account its bending deflection.

The unit cost of the intermediate support \( C_{i} \) depends on its design and height \( H_{i} \). In [8] statistical analysis of data on the cost of metal intermediate supports of cable roads and power transmission lines was carried out. The results of this analysis showed that the change in the cost of the intermediate support with the change of its height could be approximated by the power law dependence:

\[
C_{i} = C_{0} H_{i}^{a},
\]

(2)

where \( C_{0} \), \( a \) – empirical coefficients obtained from statistical analysis of the cost of intermediate supports of the same type of construction.

Fatigue strength of metal structure assemblies directly receiving load from a traction-bearing cable is important in selecting structures of intermediate supports. One of effective methods of increasing the fatigue strength of plate elements of metal structures is the creation of bimetallic structures [9].

The unit cost of the foundation of the intermediate support \( C_{f} \) is proportional to the weight of the support, i.e. its height \( H_{i} \). Therefore, it is also possible to use a power regression dependence to determine cost \( C_{f} \)

\[
C_{f} = C_{f0} H_{i}^{a_{f}},
\]

(3)

wherein cost \( C_{f} \) is conveniently taken as a fixed share of cost \( C_{i} \): \( \chi = C_{f} / C_{i} \). Then the empirical coefficients in equation (3) can be defined as

\[
C_{f0} = \chi C_{0}; \quad a_{f} = a.
\]

According to safety requirements of freight aerial cableways [10], it is necessary to use double or triple wire steel strand ropes with organic core as traction and bearing ropes. In the organic core it is advisable to place integral magnetic labels to mark and control the condition of different sections of ropes [11].

The main parameters of steel ropes used in the calculations should be presented in the form of regression equations depending on the rope diameter \( d_{k} \). The least squares analysis showed that the best approximation to the source data is achieved using the following dependences:

- weight of 1 linear meter of a rope length
  \[
  q_{k} = q_{0k} d_{k}^{2};
  \]

- aggregate strength (breaking force) of a rope
  \[
  R_{k} = r_{0k} + r_{1k} d_{k} + r_{2k} d_{k}^{2};
  \]

- cost of 1 linear meter of a rope length
  \[
  C_{k} = c_{0k} + c_{1k} d_{k} + c_{2k} d_{k}^{2},
  \]

where \( q_{0k}, r_{0k}, r_{1k}, r_{2k}, c_{0k}, c_{1k}, c_{2k} \) – empirical factors derived from statistical analysis of weight, aggregate strength and cost of single-type ropes.

Figure 1 shows the design diagram of a horizontally located section of a mono-cable freight cableway between adjacent intermediate supports. The bending deflection of a carrying rope is formed under several forces: vertical uniformly distributed load from the rope’s weight with intensity \( q_{k} \),
vertical concentrated load from the weight of cargo cabins $Q_{cab}$ and the axial force of a rope tension $kT$. The weight of cargo cabins $Q_{cab}$ depends on design productivity $C_{p}$ of a cable road and the speed of a traction-bearing cable $v_k$.

![Figure 1. Design diagram of a cableway route section](image)

At present, there is a number of calculation methods to simulate rope deflection under concentrated masses, for example, [12, 13]. However, during optimization calculations it is permissible to present concentrated loads from weight of cargo cabins as evenly distributed load $q_{cab} = Q_{cab} / L_{cab}$.

Then the relation between the load of a rope and the design capacity of a cable road will be expressed by the following dependence:

$$ q_{cab} = \frac{gC_{p}}{3600v_k^2}\left(1 + \frac{P_{cab}}{G_{cab}}\right), $$

where $L_{cab}$ – distance between adjacent cargo cabins; $g$ – gravitational acceleration; $G_{cab}$ – nominal load capacity of a cargo cabin; $P_{cab}$ – dead weight of unloaded cargo cabin.

At relative rope bending deflection typical for a cable road $f / L_{k} < 0.1$ with error less than 1.3%, the geometric line of rope bending deflection between adjacent intermediate supports can be represented by the following dependence [14]:

$$ \gamma(x) = H_{k} - \frac{\psi_{d}(q_{k} + q_{cab})}{2T_{k}} x(L_{k} - x) $$

with bending deflection in the middle of a span

$$ f = \frac{\psi_{d}(q_{k} + q_{cab})L_{k}^2}{8T_{k}}, $$

where $\psi_{d}$ – dynamic factor ($\psi_{d} > 1$) [10, 15].

The length of a bearing-traction rope in a span between supports is as follows

$$ l_{k} = L_{k}\left[1 + \frac{\psi_{d}^2(q_{k} + q_{cab})^2L_{k}^2}{24T_{k}^2}\right], $$

its minimum diameter determined from the aggregate strength condition is expressed by the following dependence:

$$ d_{k} = 0.5\sqrt{\frac{r_{k}^2 - 4r_{k2}(r_{k0} - n_{k}T_{k}) - r_{k1}^2}{r_{k2}}}, $$

where $[n]_{k}$ – minimum safety factor of a rope established by safety requirements of freight aerial cable roads [10].

Taking into account the minimum permissible height approach of cargo cabins to the surface $h_{min}$ and the vertical overall size of the cabin $h_{cab}$, the geometric height of the intermediate support will be as follows:

$$ H_{tg} = h_{min} + h_{cab} + f. $$
4. Formulation of the optimization problem

The analysis of the mathematical model of a mono-cable freight ropeway makes it possible to draw the following conclusion. Two independent values shall be used as variable parameters of the optimization problem: distance between intermediate supports \(L_i\) and tension force of a bearing-traction rope \(T_k\).

The vector of controlled parameters is formed from them

\[
(x)^T = (x_1, x_2) = (L_i, T_k) \,.
\]

The remaining values in equations (1) to (8) are fixed. When you design a cable road, they are set as source data or calculated based on the specified controlled parameters \(L_i\) and \(T_k\). The first group includes: \(L_{\gamma}, L_{\text{cab}}, Q_{\text{cab}}, h_{\text{min}}, h_{\text{ub}}, \psi, p_{\gamma}, \psi_{t}, n_k, C_f, a_f, C_{f0}, a_f, q_{\text{ck}}, r_{\text{tk}}, \beta_{\text{tk}}, r_{\text{z2}}, c_{\text{z1}}, c_{\text{z2}}\). The second group includes: \(q_k, q_{\text{ub}}, f, d_k, H_{\text{tg}}, l_k, n_k\). The vector of uncontrolled parameters is formed from the second group values, which are not subject to variation in the process of solving the optimization problem:

\[
(z)^T = (z_1, z_2, z_3, z_4, z_5, z_6, z_7) = (q_k, q_{\text{ub}}, f, d_k, H_{\text{tg}}, l_k, n_k) \,.
\]

Thus, the problem of technical and economic optimization of horizontal freight aerial cableway is reduced to minimization of the objective function – the total cost of manufacturing and assembly of intermediate supports, acquisition of a load-carrying cable. According to (1), the objective function is as follows:

\[
O_{(x), (z)} = \frac{L_{\gamma}}{x_1} \left( C_{f0} \left[ h_{\text{min}} + h_{\text{ub}} + \psi_{t} (z_1 + z_2) x_1^2 \right] \right)^{a_f} +

+ C_{f0} \left[ h_{\text{min}} + h_{\text{ub}} + \psi_{t} (z_1 + z_2) x_1^2 \right] + C_{f0} + \left( \frac{L_{\gamma}}{x_1} - 1 \right) C_{f0} x_1^2 \left[ 1 + \psi_{t} (z_1 + z_2) x_1^2 \right] \rightarrow \min \,.
\]

The optimum point of the objective function (9) is found taking into account the set of requirements, which shall be considered in the design of a freight cable road. Such requirements include structural, assembling, strength, deformation and regulatory conditions. They make it possible to form the following system of limitations presented by equation-inequalities:

- limitation of the permissible range of change of the assembly step of adjacent intermediate supports
  \[x_1 \geq 0; \quad L_{\text{max}} - x_1 \geq 0; \quad L_{\text{min}} / x_1 - 1 \geq 0;\]
- limitation of the permissible range of load-traction rope diameters variation
  \[d_{\text{max}} - d_k \geq 0; \quad d_k - d_{\text{min}} \geq 0;\]
- limitation of the maximum permissible value of a bearing rope bending deflection between adjacent intermediate supports
  \[\psi_{t} x_1 = \psi_{t} (z_1 + z_2) x_1^2 \geq 0;\]
- limitation of the minimum tension force of a load-bearing cable according to safety requirements of freight aerial cable roads [10]
  \[10 - (q_{\text{ub}} + q_k) L_{\gamma} / \psi_{t} x_2 \geq 0; \quad \psi_{t} x_2 = 600 q_k \geq 0;\]
- limitation of the maximum tension force of a rope based on its maximum possible aggregate strength
  \[R_k (d_{k_{\text{max}}}) / [n_k] - x_2 \geq 0;\]
- limitation of the maximum height of an intermediate support
  \[H_{\text{tg}} - h_{\text{min}} - h_{\text{ub}} = \psi_{t} (z_1 + z_2) x_1^2 \geq 0;\]

where \(L_{\text{max}}\) – limit distance between intermediate supports; \(d_{k_{\text{max}}}, d_{k_{\text{min}}}\) – maximum and minimum cable diameters; \(R_k (d_{k_{\text{max}}})\) – aggregate strength of a cable with the maximum diameter; \(\psi_{t}\) – factor of permissible bending deflection of a cable between supports; \(H_{\text{tg}}\) – limit height of an intermediate
support; $\mu$ – ratio of minimum and maximum tension forces of a traction cable along the track of a cable road (defined as a result of traction calculation of a cable road).

5. Analysis of the results of solving the optimization problem

In order to assess the possibilities of the developed mathematical model and the optimization problem in the design of freight cable roads, we calculated the model route with length $L_r = 3$ km and cable speed $v_k = 3$ m/s for different values of productivity $C_p$ in the range of up to 600 t/h according to the data in [6] on the productivity of modern freight cable roads. For this purpose, a computer software FreightCablewayOpt was developed based on the above optimization mathematical model. The Hooke–Jeeves algorithm was used as an optimization method.

Figure 2 shows the impact of the design capacity on optimal parameters of intermediate supports. In the range of $0 \leq C_p \leq 250$ t/h, the design capacity significantly affects the step of intermediate supports along the cableway route. At large values of $C_p$, the step value $L_t$ reaches its minimum and ceases to depend on the design performance of a cable road. The optimum height of intermediate supports in the entire range $C_p$ remains almost constant. It is connected with the fact that according to dependence (8) it consists of constant values $h_{min}$ and $h_{cab}$, and the bending deflection of a rope between support $f$ is regulated by an optimum tension of a rope $T_k$ according to coefficient of admissible bending deflection $\psi_f$. The cost of technological equipment $C_e$ installed on intermediate supports strongly affects their optimal parameters. The cost component of technological equipment in dependence (1) increases with the increase in the number of intermediate supports along the route of a freight cable road, and therefore the need to minimize the cost of construction $C$ in accordance with the objective function (9) causes the need to increase the optimal step of intermediate supports (i.e. to decrease their number $n_t$). As a result, the optimum height of intermediate supports is increased due to the increase of the rope bending deflection $f$ in the span between supports.

Figure 2. Optimal parameters of intermediate supports: a – step of supports; b – height of supports (1 – $C_e$ = 0; 2 – $C_e$ = $400$; 3 – $C_e$ = $800$; 4 – $C_e$ = $1200$)

Figure 3 shows the impact of design capacity on optimal parameters of a traction cable. The cost of technological equipment $C_e$ also has a marked influence on the axial tension force of a rope $T_k$ and its diameter $d_t$. The impact is the most prominent at lower design capacity of a cable road ($C_p < 300$ t/h). At large values $C_p$, the impact of cost $C_e$ is reduced to 0. This is due to the fact that at large values of design capacity of a cable road the cost of intermediate supports and the cost of a traction-bearing rope make the main contribution to the cost of its construction.
Figure 3. Optimal parameters of a traction-bearing rope: a – rope tension; b – rope diameter (1 - \( C = 0 \); 2 - \( C = $400 \); 3 - \( C = $800 \); 4 - \( C = $1200 \))

The calculations showed that one way to further reduce the cost of construction of freight cable roads is to reduce the losses associated with the motion of a traction-bearing rope, i.e. with the increase of coefficient \( k_t \). As a result, the optimal tension of a rope \( T_k \) is reduced and a cheaper rope of smaller diameter can be used. The losses can be reduced through an approach that proved to be highly effective for stream-flow transportation with an overhead belt [16, 17]. Its aim is to abandon the central drive of a rope motion since freight cabins are equipped with individual reduction motors.

6. Conclusion

The design of mono-cable freight ropeways using the proposed optimization mathematical model can be done by analyzing the influence of a considerable number of cost, structural, geometric and strength factors on optimal arrangement, height and a number of intermediate supports, on the optimal tension force and diameter of bearing-traction ropes. This makes it possible to determine the most economical option of construction in specific conditions taking into account high-altitude characteristics of a relief along the cable road route, cost of various design options of intermediate supports, technical characteristics of load-carrying and traction ropes, etc. The results of this optimization task allows significantly reducing the cost of construction of freight aerial cableways.

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