V.A. Malinovsky[1] and N.A. Tarnavskaya[2] **ODN 0794**
[1]"Vira-Service Plus, Ltd.", Odessa, Ukraine

[2]National Polytechnic University of Odessa, Odessa, Ukraine

Adapted hoist ropes

Summary

This paper consolidates experience in the development and commercial tests of variable lay length mine shaft hoist ropes in Ukraine during 2001-2005.

1 Description of the problem

Torsion of the twisted wire rope in the vertically suspended long ropes is one of major headaches for designers and mine shaft engineers if the shaft is sufficiently deep. In principle, this problem impacts considerably the service life of the hoist rope starting from the lifting depth in excess of 500 m.

From a physical viewpoint, the problem is that a twisted rope responds to a change of its tension along its length, caused by the self weight, in a peculiar way, which, in our case, is described by a linear law

$$T(x) = Q + p(L - x)$$

where Q – end load weight; p – self weight of the rope unit length; L – length of the rope; x – length co-ordinate to be measured from the sheave downward.

The point is that the rope torque is proportional to tension and depends on the lay parameters (primarily on the angles and lay lengths of strands and the rope)

$$M \propto T(x) \cdot \Gamma(x)\,, \qquad (1)$$

where $\Gamma(x)$ – is a generalized function of the lay parameters, i.e. rope geometry.

Besides, in the absence of extraneous torsional impacts along the rope length

$$M = const\,. \qquad (2)$$

As the tension $T(x)$ in (1) varies along the length, then, in order to meet the condition (2), the rope changes its geometric function $\Gamma(x)$ by itself so that the condition below is observed:

$$T(x) \cdot \Gamma(x) = const\,.$$

Physically, it means that the rope lowered down into the mine shaft rotates around its axis until its geometry meets the requirement (2). It is this feature that makes the major difference in the working conditions of the shaft ropes and other ropes that are characterised by a great difference in height of the attachment points, e.g., of the overhead ropeways and ropes of the general industrial applications.

This phenomenon has been theoretically considered by Prof. M.F. Glushko in his extraordinary monograph [1]. We shall remind the reader of the theoretical fundamentals for the case of the mine section with a load in the guides.

1. Calculation diagram and curves of torsional displacements and deformations are shown in Figure 1.

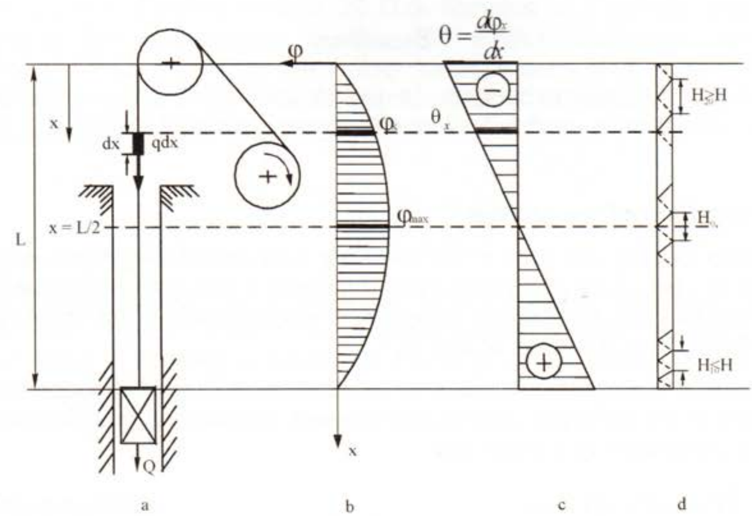


Figure 1: Diagram of shaft hoisting rope performance: a – hoist diagram; b – turn angles curve; c – torsional deformation curves; d – diagram of lay length variation.

2. Twisting of the vertical section of the rope is caused by its self weight only and does not depend on the end load value. Rotation angles of the rope cross sections follow the parabolic law, the maximum being in the mid length of the rope while gradually reducing to zero to the rope ends.

3. Tensile deformation of the rope

$$\varepsilon = \frac{1}{A}\left(Q + \frac{1}{2}pL\right) + \frac{B}{2\Delta}p(L-2x),$$

where $\Delta = AB - C^2$; A, B, C – stiffness coefficients of the rope adopted at calculation: (see [1]):

A – longitudinal stiffness; B – torsional stiffness; C – impact factor;

4. Torsional deformation of the rope

$$\theta = -\frac{C}{2\Delta}p(L-2x).$$

The maximum rotation angle is at $x = \frac{L}{2}$, i.e., in the middle of the rope

$$\varphi_{\max} = -\frac{C}{\Delta}\frac{pL^2}{8}.$$

The maximum torsional deformation is recorded at the rope ends

$$\theta_{\max} = \pm\frac{C}{2\Delta}pL = \pm\frac{4\varphi_{\max}}{L},$$

wherefrom

$$\varphi_{\max} = \pm\frac{1}{4}L\theta_{\max}\ . \tag{3}$$

5. The upper half of the rope is untwisting as the lay length is increased while the lower half, on the contrary, is twisting as the lay length is reduced. The middle section does not suffer torsion and preserves the rated lay length H_0. Rope twist is accompanied with a considerable (primarily, unfavourable) re-distribution of the loads among the rope elements, which reduces the rope service life.
6. At the equilibrium condition the rope acquires a variable lay length $H(x)$ that increases from the lower end of the rope towards the top end.
7. In the drum section the variable lay length is fixed and the rope continues to work there with a variable lay length.
8. It should be noted, that in the case of a friction sheave (Koepe) hoist the said torsion is cyclic, i.e., at each lifting/lowering either half of the rope is subjected to a full cycle of twisting and untwisting, and therefore a variable lay length rope is not suitable for this application.

2 Conventional technical solutions

Conventionally, two methods to overcome the considered phenomenon are applied in the mine shafts:

1. Application of non-spin ropes, mainly 3-layer oval strand ropes, that are not liable to this phenomenon. This method is chosen by specialists of the leading West European companies.
2. On the contrary, in deep mines of the South African Republic (to 2,500 m) they make use of spin Lang's lay triangular strand ropes wherein the lay length variation in operation reaches 100%. The point is that these ropes are rather twist-resistant, i.e., variations of their strength and other physical and mechanical properties are little. It has been established during special studies [2], that if the lay lengths vary within (-30%) – (+80 %) range, the strength of triangular strand ropes varies from -10 to +3 %.

3 Novel technical solution

A novel solution was suggested by a famous German specialist R. Verreet who invented the variable lay length wire rope intended for use in suspended rope lengths characterised by a great height difference between their ends, specifically for mine hoists, deep-water hoists or overhead ropeways (Germany patent DE 3632298 A1 dated 23.09.1986). In 2001, specialists of the PJSC "Stalkanat", Ukraine, launched an independent study and came to a similar technical solution so that, starting from 2001, the variable lay length ropes were used in deep iron ore mines of Krivoy Rog. Thus, the authorship and invention of the variable lay length ropes belong to R. Verreet while the first industrial application of such ropes was accomplished by Ukrainian specialists [3].

The idea of this novel technical solution is extremely simple: if the hoisting rope "wishes" to have a variable lay length (shortened at the bottom and lengthened at the top) in the mine shaft in order to be in equilibrium, then we need to "assist" it by manufacturing such a variable lay length rope from the very beginning.

Under these circumstances, the rope lowered in the shaft acquires equilibrium condition as to torsion at once without any considerable variations in the twist parameters, and consequently, without any variation in the stress-and-strain condition of wires as compared to the design.

We emphasise a difference of principle between the rope of variable lay length resulting due to twisting in the mine shaft caused by the self weight and the similar rope of variable lay length obtained at manufacturing. The first rope is under a great internal stress caused by twisting, and the second rope is in its natural condition.

How should the lay length vary in the course of manufacturing? Ideally, it must change continuously, following the pattern of variable lay length formation in the rope due to twisting in the mine shaft.

The law describing the lay length variation may be obtained as follows. A variable lay length rope has variable stiffness coefficients which we designate as $\tilde{A},\tilde{B},\tilde{C}$. Then, the known equilibrium equations for the vertically suspended heavy rope [1] are:

$$\begin{aligned} \tilde{A}\varepsilon + \tilde{C}\theta &= T(x) = Q + p(L-x) \\ \tilde{C}\varepsilon + \tilde{B}\theta &= M = const. \end{aligned} \tag{4}$$

Now we need that the entire rope length does not suffer twisting, i.e., we assume $\theta = 0$. Then, it follows from (4)

$$\frac{\tilde{C}}{\tilde{A}}T(x) = M = const. \tag{5}$$

As a first approximation, the ratio $\frac{\tilde{C}}{\tilde{A}} \approx r_0 tg\beta = 2\pi \frac{r_0^2}{H(x)}$ describes a single-layer round strand rope, where r_0, β and $H(x)$ – are the radius, angle and strand lay length, respectively. So, the condition (5) may be written as follows:

$$\frac{\tilde{C}}{\tilde{A}}T(x) \approx 2\pi \frac{r_0^2}{H(x)}T(x) = const ,$$

wherefrom, leaving the variable values only, we obtain the condition

$$\frac{T(x)}{H(x)} = const\ .$$

Considering that the mid rope ($x = \frac{L}{2}$) does not twist anyway, and accepting for this case the cross sections $\frac{T_0}{H_0} = \frac{Q + \frac{1}{2}pL}{H_0}$, we finally obtain $\frac{T(x)}{H(x)} = \frac{T_0}{H_0}$,

wherefrom

$$H(x) = H_0 \frac{T(x)}{T_0} = H_0 \frac{Q + p(L - x)}{Q + \frac{1}{2}pL}. \qquad (6)$$

Thus, from Equation (6), the rope lay length must be proportionate to its tension.

Now we consider an example of the actual hoist in the shaft, namely, a ∅ 42.0 mm rope made to GOST 7669-80, constructed as 6x36(1+7+7/7+14)+7x7(1+6), sZ, H_0 = 270 mm; p = 79.65 N/m, L = 1,340 m, Q = 122.5 kN. Let us determine the required lay length in the upper cross section (x = 0) according to Equation (6):

$$H(0) = 270 \frac{122{,}500 + 79.65 \cdot 1{,}340}{122{,}500 + \frac{1}{2} 79.65 \cdot 1{,}340} = 352\ mm\ ,$$

the lay length in the lower cross section is $(x = L)$

$$H(L) = 270 \frac{122{,}500}{122{,}500 + \frac{1}{2} \cdot 79.65 \cdot 1{,}340} = 188\ mm\ .$$

So, in this particular case the lay lengths in the rope ends should differ from the rated lay length in the mid cross section by ±30%. We are of the opinion that such first estimation of overrated as the calculation does not take account of the inter-wire friction in the rope and a number of other factors. Let us leave this issue for a further study.

By way of illustrating the above thesis of the basic difference between the variable lay length ropes obtained either by twisting or by laying, we submit Figure 2 indicating the normal stress curves in the wires of two similar ropes ∅ 42.0 mm as per GOST 7669. Figure 2a shows the curves of a standard rope made with a constant lay length H_0 = 270 mm, and Figure 2b depicts the similar rope made with a variable lay length in accordance with the above calculation, i.e., $H(x) = 352 \div 188$ mm. The stresses in the wires have been determined by PC computation according to a known method [4].

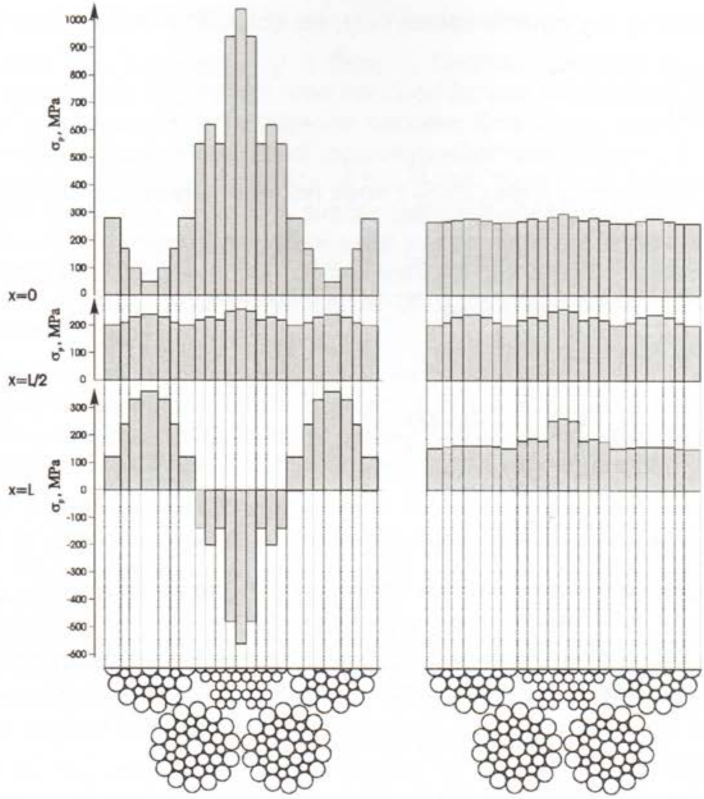


Figure 2: Curves of normal tensile stresses in the cross sections x=0; x=L/2; x=L of the ropes: a – as per GOST 7669-80 (rope lay length 270 mm); b – with a variable lay length H = 352÷188 mm.

It is evident that the stressed conditions of these two ropes differ drastically. With the standard rope, Figure 2a, the steel core is considerably overloaded in the upper cross section while the lower cross section suffers an axial compression. These curves explain the practically observed cases when the core broke at the top and the core came out of the rope at the bottom. The variable lay length rope, Figure 2b, is decisively superior as to the uniform loading of its elements.

Certainly, it is not always possible to adhere to design guidelines under actual production conditions. First, the rope-twisting machines are not provided for the most part with a device for continuous lay length change. Second, the calculated parameters obtained should be additionally verified by design considerations so as to exclude, for example, a loose rope structure at an excessively long lay length.

This proposal may be most probably accomplished, both technically and practically, by a discrete alteration of the lay length along the rope. It is quite possible that a rope may "twist through by itself", reaching the continuous lay length change, after it has been hoisted in the mine shaft. Figure 3 presents a line illustrating a staged lay length along the rope as delivered as well as a probable line illustrating a continuous variation of the lay length due to twisting after the first lowering of the rope in the shaft (see the dashed line).

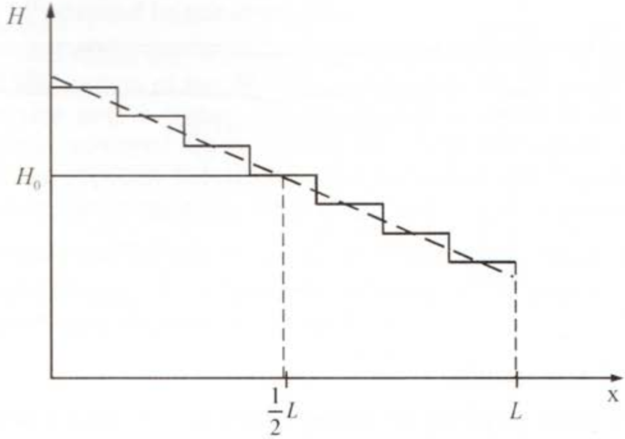


Figure 3: Rope lay length change: discrete, by sections, as delivered – solid line; continuous, after hoisting – dashed line.

4 Construction and technical parameters of the ropes

New-type ropes have been developed for deep mines of Krivoy Rog to replace the ropes as per GOST 7669 of the construction 6x36(1+7+7/7+14)+IWRC(7x7(1+6)), dia. 60.5 mm, manufactured by Volgograd Steel Wire Rope Plant. After the break up of the USSR there appeared difficulties in procuring such ropes from Volgograd and it became necessary to set up heavy steel wire rope production in Ukraine.

Taking guidance of the construction and processing considerations, it was decided to choose, as the basis, the 8-strand rope construction. However, the 8-strand ropes are susceptible to twisting to a still greater degree than the 6-strand ropes. Specialists know this well. It is the necessity to overcome this drawback that has led to the idea of making these ropes with a variable lay length, which suits their future application: the shortest lay length – at the lower end, and the longest – at the upper end of the rope. The rope length was 1,460 m and the net mass – 23,700 kg.

The rope construction and the wire diameters are given below:

$$8 \times 36\left(\frac{1}{3.20}+\frac{7}{2.40}+\frac{7}{2.30}\Big/\frac{7}{1.80}+\frac{14}{2.80}\right)+6 \times 19\left(\frac{1}{2.15}+\frac{6}{2.05}+\frac{6}{2.5}\Big/\frac{6}{1.65}\right)+F.C.$$

The rope has a right-hand ordinary lay sZ, the core has a right-hand Lang's lay zZ. The core lay length is 160 mm. The nominal diameter of the rope is 60.5 mm and the actual diameter at delivery is 64.0 mm. The construction cross sectional area of all wires in the rope totals 1,730 mm^2. Approximate mass of 100 m of rope length is 1,623 kg. Ropes are made of galvanized wire of grade 1,770 N/mm^2. The aggregate breaking load of all wires is at least 3,060 kN, and the breaking load of the entire rope is at least 2,450 kN.

In accordance with the mine shaft dimensions and the hoisting machinery parameters, the ropes have been manufactured with a staged lay length change as follows:

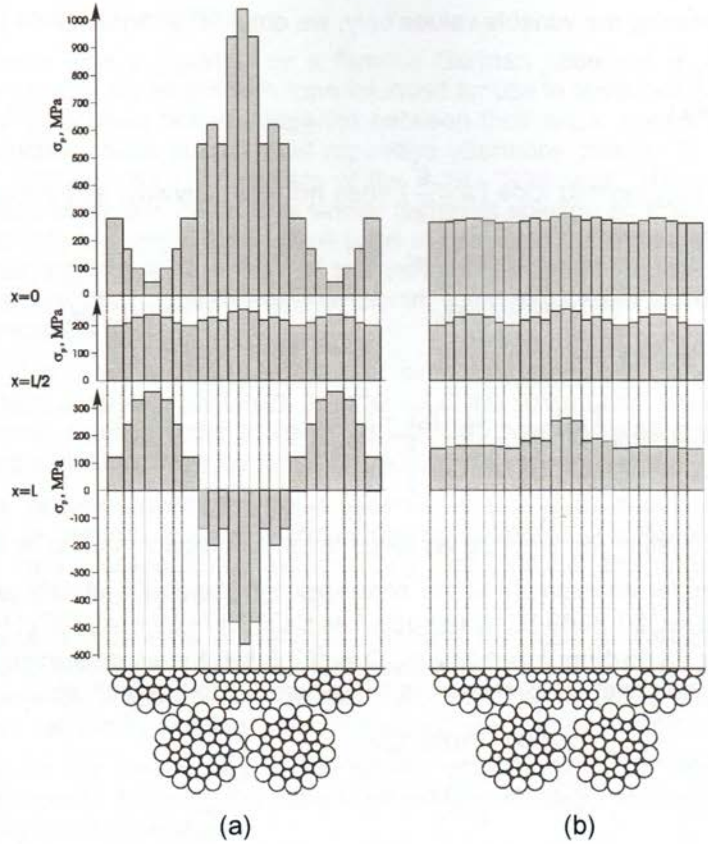


Figure 2: Curves of normal tensile stresses in the cross sections x=0; x=L/2; x=L of the ropes: a – as per GOST 7669-80 (rope lay length 270 mm); b – with a variable lay length H = 352÷188 mm.

It is evident that the stressed conditions of these two ropes differ drastically. With the standard rope, Figure 2a, the steel core is considerably overloaded in the upper cross section while the lower cross section suffers an axial compression. These curves explain the practically observed cases when the core broke at the top and the core came out of the rope at the bottom. The variable lay length rope, Figure 2b, is decisively superior as to the uniform loading of its elements.

Certainly, it is not always possible to adhere to design guidelines under actual production conditions. First, the rope-twisting machines are not provided for the most part with a device for continuous lay length change. Second, the calculated parameters obtained should be additionally verified by design considerations so as to exclude, for example, a loose rope structure at an excessively long lay length.

This proposal may be most probably accomplished, both technically and practically, by a discrete alteration of the lay length along the rope. It is quite possible that a rope may "twist through by itself", reaching the continuous lay length change, after it has been hoisted in the mine shaft. Figure 3 presents a line illustrating a staged lay length along the rope as delivered as well as a probable line illustrating a continuous variation of the lay length due to twisting after the first lowering of the rope in the shaft (see the dashed line).

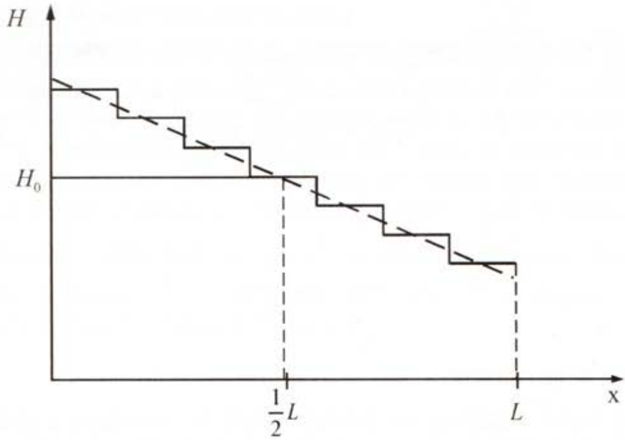


Figure 3: Rope lay length change: discrete, by sections, as delivered – solid line; continuous, after hoisting – dashed line.

4 Construction and technical parameters of the ropes

New-type ropes have been developed for deep mines of Krivoy Rog to replace the ropes as per GOST 7669 of the construction 6x36(1+7+7/7+14)+IWRC(7x7(1+6)), dia. 60.5 mm, manufactured by Volgograd Steel Wire Rope Plant. After the break up of the USSR there appeared difficulties in procuring such ropes from Volgograd and it became necessary to set up heavy steel wire rope production in Ukraine.

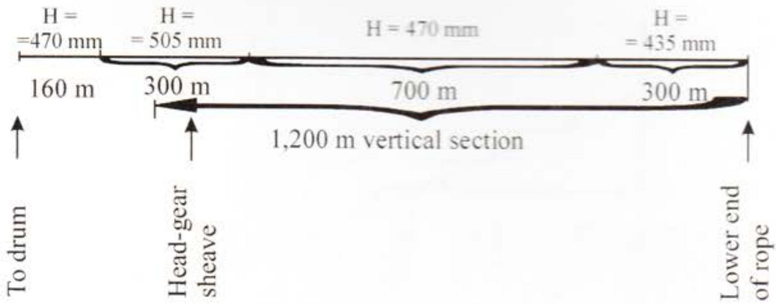
Taking guidance of the construction and processing considerations, it was decided to choose, as the basis, the 8-strand rope construction. However, the 8-strand ropes are susceptible to twisting to a still greater degree than the 6-strand ropes. Specialists know this well. It is the necessity to overcome this drawback that has led to the idea of making these ropes with a variable lay length, which suits their future application: the shortest lay length – at the lower end, and the longest – at the upper end of the rope. The rope length was 1,460 m and the net mass – 23,700 kg.

The rope construction and the wire diameters are given below:

$$8\times 36\left(\frac{1}{3.20}+\frac{7}{2.40}+\frac{7}{2.30}\Big/\frac{7}{1.80}+\frac{14}{2.80}\right)+6\times 19\left(\frac{1}{2.15}+\frac{6}{2.05}+\frac{6}{2.5}\Big/\frac{6}{1.65}\right)+F.C.$$

The rope has a right-hand ordinary lay sZ, the core has a right-hand Lang's lay zZ. The core lay length is 160 mm. The nominal diameter of the rope is 60.5 mm and the actual diameter at delivery is 64.0 mm. The construction cross sectional area of all wires in the rope totals 1,730 mm^2. Approximate mass of 100 m of rope length is 1,623 kg. Ropes are made of galvanized wire of grade 1,770 N/mm^2. The aggregate breaking load of all wires is at least 3,060 kN, and the breaking load of the entire rope is at least 2,450 kN.

In accordance with the mine shaft dimensions and the hoisting machinery parameters, the ropes have been manufactured with a staged lay length change as follows:



5 Industrial test results

The ropes have been installed on similar hoists of the double drum winder at the mines "Artem-1" and "Oktyabrskaya" in Krivoy Rog. The conditions and results of industrial tests are shown in Table 1.

Mine	Hoist type	Loaded conveyance kg	Empty conveyance kg	Counter-weight kg	Date		In-service period, tonnage, cause of removal
					of installation	of removal	
Artem	skip-south	29,700	12,700		28.08.2001	8.03.2003	18 months 1,100,000t. ΔS = 23%
Artem	skip-north	29,700	12,700		28.08.2001	03.03.2003	18 months 1,100,000t. ΔS = 17%
Artem	skip-south	29,700	12,700		02.04.2003	06.04.2004	12 months 800,000t. ΔS = 17%
Artem	skip-north	29,700	12,700		08.03.2003	06.04.2004	12 months 800,000t. ΔS = 19%
Artem	Cage - 1	18,000	12,700	18,000	22.04.2002	19.04.2005	36 months mechanical property of wire ΔS = 11%
Artem	Counter-balance -1			18,000	22.04.2002	29.04.2005	36 months mechanical property of wire ΔS = 10%
Artem	Cage - 2	18,000	12,700		25.03.2003		Aug. 2005 in work ΔS = 7%
Artem	Counter-balance -2			18,000	12.10.2002		Aug. 2005 in work ΔS = 6.5%
Oktyabr-skaya	cage	16,000	9,000	16,000	03.2004		Aug. 2005 in work ΔS = 6%
Oktyabr-skaya	Counter-balance			16,000	03.2004		Aug. 2005 in work ΔS = 6%

Note: ΔS is loss of metallic area.

Table 1: Summary of service performance of variable lay length ropes.

6 Twisting of adapted in-service ropes

The above described ropes with a discrete lay length variation are not yet ideal in the sense of the full elimination of the vertical section twist. It is clear, that the rope will twist more in service until a certain equilibrium with a continuously (monotonously) variable lay length is achieved. Such twisting will modify a stressed condition of wires along the rope cross sections, therefore it must be known and calculable. A simplified method to calculate the variable lay length rope twist $H(x)$ is presented. Such rope has variable stiffness coefficients $\tilde{A}$, $\tilde{B}$, $\tilde{C}$ (a physical meaning is according to [1]): $\tilde{A}$ – longitudinal stiffness; $\tilde{B}$ – torsional stiffness; $\tilde{C}$ – impact coefficient). The diagram of the shaft rope is shown in Figure 4.

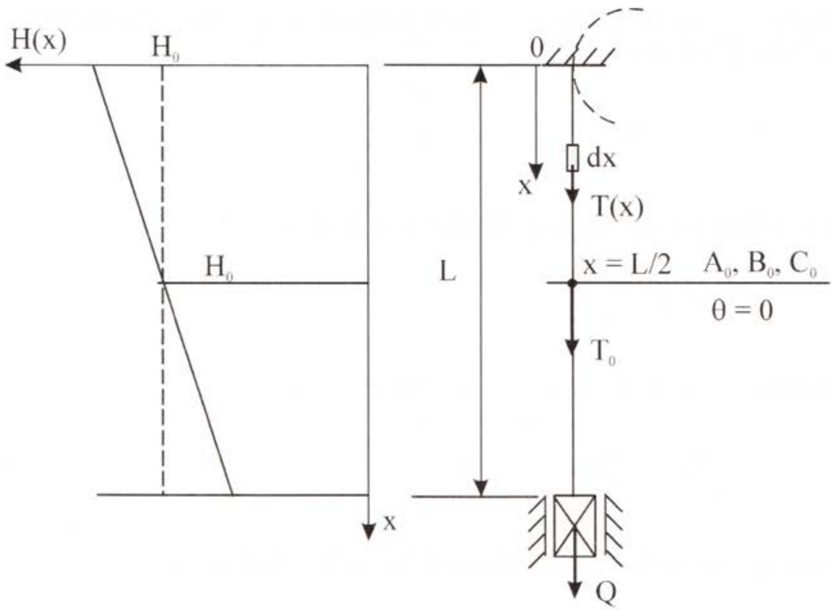


Figure 4: Diagram of the variable lay length mine rope.

As applied to the element dx, equilibrium equations [1] may be written down:

$$\begin{aligned} \tilde{A}\varepsilon + \tilde{C}\theta &= T(x) = Q + p(L - x) \\ \tilde{C}\varepsilon + \tilde{B}\theta &= M = const \end{aligned} \tag{7}$$

where ε and θ are relative tensile and torsional deformations of the rope.

At this stage we assume $p = const$, neglecting a minor change of the linear density along the rope length.

The torque can be easily found for the middle of the vertical section where $\theta(L/2) = 0$:

$$M = \frac{C_0}{A_0} T_0 = const. \tag{8}$$

Let us solve (7) with due account of (8) relative to twisting which we consider theoretical:

$$\theta_T = \frac{\widetilde{C}}{\widetilde{C}^2 - \widetilde{A}\widetilde{B}} \left(Q + p(L-x) - \frac{\widetilde{A}}{\widetilde{C}} \frac{C_0}{A_0} T_0 \right). \tag{9}$$

As the functions $\widetilde{A}$, $\widetilde{B}$, $\widetilde{C}$ are known (these may be either given or calculated on the basis of the given twist parameters), a torsional deformation function $\theta(x)$ can be found from (9). Clearly the absolute twist (angular turn of the cross section) may then be determined by integration:

$$\varphi(x) = \int_0^x \theta(x) dx.$$

Variation in the rope lay length at tension and twisting [1]

$$\Delta H = H \cdot \varepsilon - \frac{H^2}{2\pi} \theta. \tag{10}$$

Tensile deformation from the second equation of (7) is

$$\varepsilon = \frac{C_0}{A_0 \widetilde{C}} T_0 - \frac{\widetilde{B}}{\widetilde{C}} \theta, \tag{11}$$

consequently, the lay length increment in the torsion function is

$$\Delta H = \left(\frac{C_0}{A_0 \widetilde{C}} T_0 - \left(\frac{\widetilde{B}}{\widetilde{C}} + \frac{H}{2\pi} \right) \theta \right) H. \tag{12}$$

It is evident that the new lay length that is acquired in operation equals

$$H^S(x) = H^{man.}(x) + \Delta H, \tag{13}$$

where $H^{man.}(x)$ – lay length of the rope as delivered by the manufacturer.

In actual practice of rope operation, the values $H^S(x)$ and ΔH are easily determined by measurements. Therefore, they make it possible to calculate torsional deformation of the rope from (12):

$$\theta_S = -\frac{2\pi \widetilde{C}}{2\pi \widetilde{B} + H\widetilde{C}} \left(\frac{\Delta H}{H} - \frac{C_0}{A_0 \widetilde{C}} T_0 \right) \tag{14}$$

and the tensile deformation on the basis of (11). Torsion as per (14) is experimental (tests) as it is determined on the basis of tested values of ΔH.

Let us analyse now the actual rope that has, at delivery, a discretely changing lay length (see Section 4). The vertical hoist in the shaft is $L \approx 1200\,\text{m}$. The rope performance conditions exemplified by the skip hoist of "Artem" are: the vertical hoist length - $L \approx 1200$ m; the empty skip weight – 12.7 t; the loaded skip weight – 29.7 t; and the vertical hoist rope weight is 19.1 t.

The rope has three sections along the said length, each characterized by various lay lengths, Fig. 5.

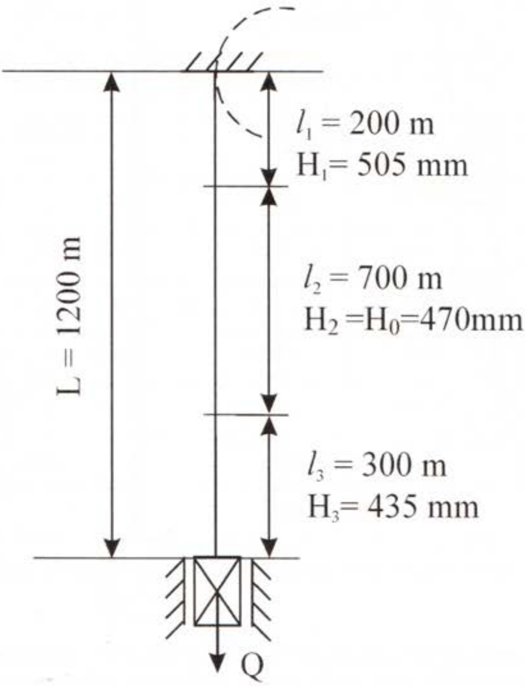


Figure 5: Diagram of the mine hoist with discretely changing lay length.

Figures 6 and 7 are diagrams of the actual lay lengths of two ropes constructed by the results of instrumental measurements taken directly in the mine shafts [5].

These diagrams present the material for a deep analysis of the stress-strain condition of ropes under given operation conditions and for further improvements of such ropes.

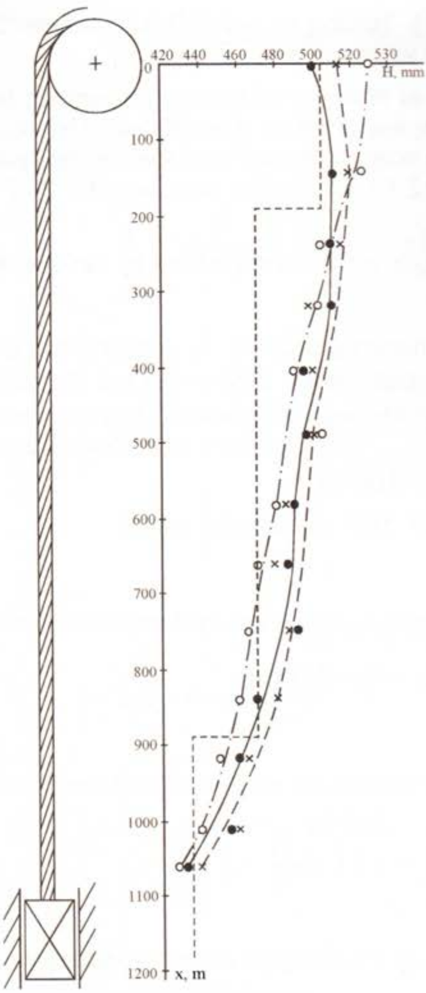


Figure 6: Diagrams illustrating the rope lay length variation in "Oktyabrskaya" mine shaft (6 months after hoisting).

- counterweight upward
- cage upward
- cage downward
- as delivered condition

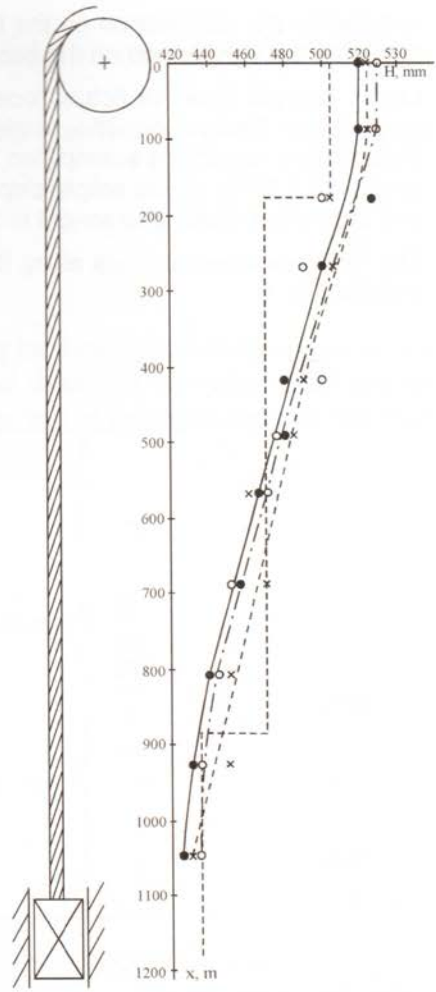


Figure 7: Diagrams illustrating the rope lay length variation in "Artem" mine shaft (29 months after hoisting).

- counterweight upward
- cage upward
- cage downward
- as delivered condition

We draw attention, meanwhile, to two circumstances. First, as it was expected, the rope in the mine shaft "twists through" until its equilibrium condition is reached so that the initial, as delivered, staged variation of the lay length is replaced with a relatively uniform reduction of this parameter from the top end of the rope towards the lower end. The second circumstance is due to the fact that the maximum values of torsional deformation of the rope should be expected not at the ends of the vertical rope section but at the points of the staged lay length change at manufacturing (at the section joints) where the relative lay length changes $\Delta H / H$ are maximum. In this particular case these are the rope section with approximate co-ordinates of x = 200 m and x = 900 m.

Table 2 consolidates the results of determination of the theoretical twist of the rope according to (9) and of the test twist according to (14), obtained by measuring the actual lay lengths in Figure 7. We submit also the maximum torsional displacement values for the middle of the vertical rope section that have been determined according to (3) on the basis of the theoretical and experimental values of torsional deformations θ_{max}.

Parameter	Section 1		Section 2		Section 3	
	x = 0 m	x = 200 m	x = 200 m	x = 900 m	x = 900 m	x = 1,050 m
$\tilde{A},[H]$	$2.765078 \cdot 10^{8}$		$2.724808 \cdot 10^{8}$		$2.668158 \cdot 10^{8}$	
$\tilde{B},[H \cdot mm^2]$	$7.524432 \cdot 10^{9}$		$8.686098 \cdot 10^{9}$		$1.034482 \cdot 10^{10}$	
$\tilde{C},[H \cdot mm]$	$1.402803 \cdot 10^{9}$		$1.493261 \cdot 10^{9}$		$1.60698 \cdot 10^{9}$	
$H_{man.}, mm$	505	505	470	470	435	435
$H_{serw.}, mm$	530	510	510	435	435	430
$\Delta H, mm$	25	5	40	-35	0	-5
$\theta_T, 1/m$	-0.961	-0.560	-0.684	0.544	0.271	0.489
$\theta_S, 1/m$	-0.567	-0.105	-1.045	0.933	0.01	0.161
$\varphi_{T\ max}$	288.3 ≈ 46 turns					
$\varphi_{S\ max}$	213.75 ≈ 34 turns					

Table 2: Summary of the results of the theoretical and experimental twist of the rope.

It is worth emphasising a peculiarity of these calculations, i.e. the fact that at the section boundaries (at x = 200 m and x = 900 m) two values of θ_T and θ_S have been obtained, which is due to a staged lay length variation in these points during manufacturing. However, in an actual rope, the torsional function may not be physically discontinuous. Therefore, we shall assume the arithmetical mean of the twist in the section boundaries:

$$\theta_T\big|_{x=200} = -\frac{0.560 + 0.684}{2} = -0.622; \qquad \theta_S\big|_{x=200} = -\frac{0.102 + 1.045}{2} = -0.575$$

$$\theta_T\big|_{x=900} = \frac{0.544 + 0.271}{2} = 0.407; \qquad \theta_S\big|_{x=900} = \frac{0.933 + 0.01}{2} = 0.471.$$

Taking into account these mean values of torsion, we show in Figure 8 the torsional deformation curves θ and angular displacement curves φ along the length of the vertical rope section string. As can be seen, the experimental values of θ_S and φ_S are smaller in magnitude than the theoretical θ_T and φ_T (except for θ_S in the section

$x = 570 \div 900\,m$, where θ_S is slightly greater than θ_T). This is logical as the theoretical computation within the frame of a purely elastic computation model gives higher results of deformations because the influence of the inter-wire friction in the rope is not accounted for.

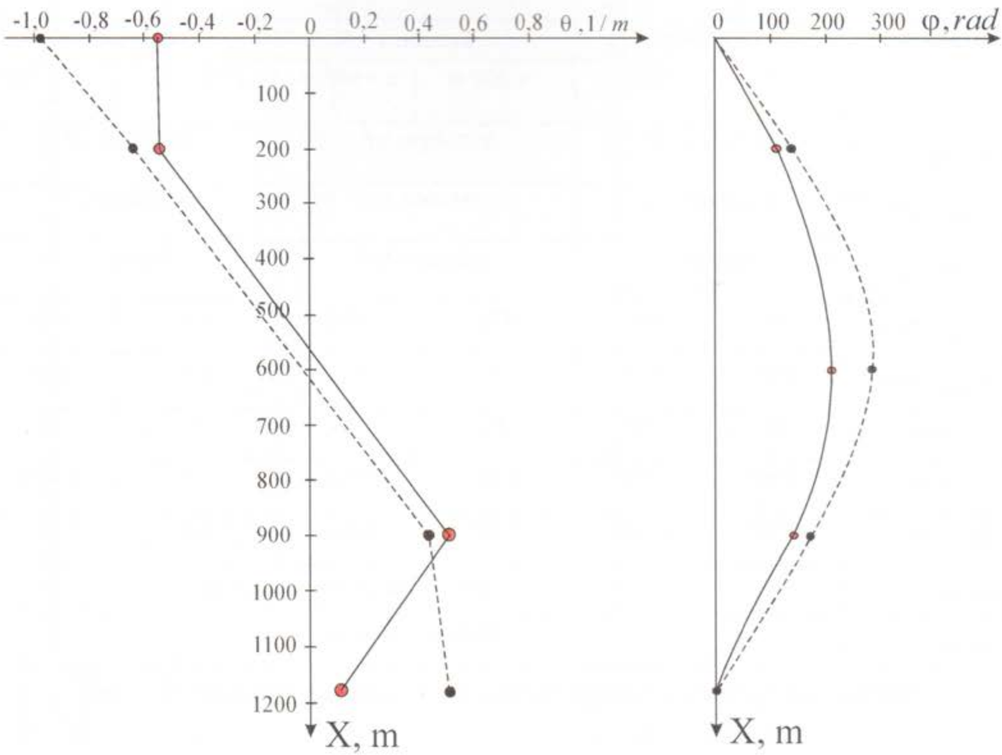


Figure 8: Torsional deformation, θ, and displacement, φ, curves: ------ - theory, —— - experiment.

Rotation of the average cross section of the rope φ_{max} is the integral indicator of the rope twist in the mine shaft. This indicator comprises $\varphi^S_{max} = 213\,rad \approx 34\,turns$ according to experimental data, and $\varphi^T_{max} = 288.3\,rad \approx 46\ turns$ according to theory.

These values of φ_{max} are shown in Figure 9 as compared to the calculated φ_{max} values for a similar rope with the constant lay length H = 470 mm along the entire length, and for a 6-strand rope as per GOST 7669, diameter 60.5 mm, construction 6×36(1+7+7/7+14)+7×7(1+6), with a constant lay length *H* = 390 mm.

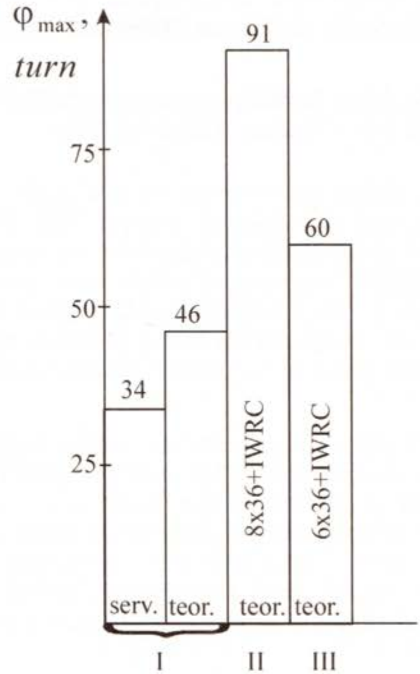


Figure 9: φ_{max} values for ∅ 60.5 mm ropes: I – 8-strand rope with variable lay length; II – 8- strand rope with H = 470 mm = const; III – 6- strand rope with H = 390 mm = const.

It is evident from Figure 9 that the application of the variable lay length at manufacturing of the rope gives a 2-3 times reduction of the rope twist as compared to a similar constant lay length rope. In combination with the uniform distribution of loads in the cross section (see Figure 2), it ensures a considerably longer service life of adapted ropes, which has been confirmed in the course of commercial operation of these ropes in Krivoy Rog iron ore mines.

Further improvement of the adapted ropes may be achieved by optimising the pattern and parameters of the lay length variation as well as by improving the rope constructions.

7 References

1 Glushko, M.F. *Steel wire hoisting ropes*, Kiev, "Technika". 1966, 327 p.

2 Rebel, G. *The torsional behaviour of triangular strand ropes for drum winders*, OIPEEC Conference Proceedings "The application of endurance prediction for wire ropes", The University of Reading, September 1997, p. 135-160.

3 Malinovsky, V.A., Malyavitsky, N.F. and Mishchenko, A.A. *Adapted mine hoisting ropes with variable lay length*, Stalnye kanaty. Issue 3. Odessa. Astroprint. 2003, p. 9-21.

4 Malinovsky, V.A., Chish, A.A. and Prigoda, A.A. *Analysis of steel wire rope with regard to geometric and force imperfections*, OIPEEC Bulletin No. 63, 1992, p. 61-73.

5 Tarnavskaya, N.S. *Mine hoisting ropes with variable lay length – first results*, Bull. IASRR. Issue 7-8., Odessa, Astroprint, 2004.