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SOME THEORETICAL CONSIDERATION ON A DEGREE OF SAFETY FOR HOISTING ROPES

Summary. Values of factor of safety for hoisting ropes applied in hoist installations are actually under review in some countries. The paper deals with the problem of rope safety measure understood as the probability of occurance of catastrophic event - the rope rupture. Two basic rope parameters tenacity and stress are taken under consideration. Their stochastic character is taken into account. Some brand new results are obtained, quite different than those usually considered up to now. The paper shows a formula for determination of hoist rope de degree of safety which allows in turn for calculation of the moment in which rope should be withdrawn.

1. INTRODUCTION

Ropes applied in hoist installations are quite grateful object of consideration which can be proved by many thick volumes of conference proceedings ([16,17] for example) and a lot of papers published occasionally ([5,7,8,11-13] for instance). On the other hand, their curiousity relies on the fact that increasing knowledge about them is still insufficient to solve in a proper way many basic problems associated with their application in mine practice. Here as an example the problem of safety assessment of hoist rope employed in mine hoisting installation can be taken into account.

This problem is strange from the very begining. "Safety" is a prime term which can be considered in two ways, at least. As the psychological term describing subjective feeling being free from danger (secure, unharmed). It can be considered also as a lack of risk or free from risk of occurance of random event treated as a danger one. Safety has relative character because "absolute" safety does not exist. In practice, there is always a certain risk of appearance of events being hazardous from a different point of view. So, this state-of-art needs a measure of its magnitude.

It was stated a long time ago, at the very begining of the theory of safety [15,20] that the objective measure of safety is the probability of occurance of catastrophic event. This probability is used to be termed as a degree of safety [9,10].

The theory of safety came into being on the field of structure safety [9,10,15,20]. Just recently development of the theory of reliability resulted in separation from its field of a special scope of consideration - safety reliability associated with the theory of systems. Generally, safety has just became an interdisciplinary sphere of its own life.

Before the probabilistic origin, on the field of strucute safety the term "factor of safety" has been formulated. Its definition "the ratio between the ultimate stress in a member, stucture, or material and the safe permissible stress in it" one can find everywhere: in dictionary [3], handbook [18], in scientific papers [11,13] dealing just with safety problems of hoist ropes and many others [1,4] . Although it has been proved a long time ago that conventional safety measures - like factor of safety - are univocal (i.e. assuring in constructions the same factor of safety we do not assure identical degree of safety)[9], their application is still wide because of convenience and ease in application. Hoisting ropes are best examples of such a statement. Apllying factor of safety we have no idea how far in reality we are from the rope rupture or saying more precisely - what is the probability of rope rupture in a given moment of hoist rope operation. On the other hand, being aware of the fact that our knowledge on real rope state is poor we apply high values for factor of safety (for all events) causing excessive overdimention in hoist installations. The South African mining industry is actually the best aware of this fact [2,19]. So, these attempts trying to determinate the degree of rope safety (again, probability of occurance of rope rupture) should be considered attentively.

2. MODEL OF ROPE WEAKENING

There have been some trials to construct models of hoist rope safety measures basing on different phenomena. In paper [8] for instance, three safety measures are presented taking into account:

- the stream of wire breaks in time,
- the distribution of wire breaks on rope length,
- the number of broken wires on few rope leads.

Here there is a new model considering at first rope degradation in time of its exploitation in shaft.

Let us assume that we have a new hoist rope, its tenacity (tensile strength) is known and its value is x_0 (the value obtained from a test). The rope is put into service and its wearing process is running in time. The real value of rope tenacity is X and is treated as a random variable (all random variables will be marked by capital letters). It is assumed that $x \leq x_0$ (neglecting any possible short period of rope strengthening just after its putting into service). Expected course of rope weakening is usually shown like in Fig.1 [12].

Assumption. The course showing rope tenacity mean value droppage in time is an ellipse sector i.e.

$$\left(\frac{x}{x_o}\right)^2 + \left(\frac{t}{b}\right)^2 = 1, \qquad \text{Fig.2,} \qquad (1)$$

for $b > t \geqslant 0$, $0 < x \leqslant x_o$ or

$$x = \sqrt{x_o^2 - \frac{x_o^2\, t^2}{b^2}} \quad .$$

Magnitudes t (parameter, time) and x_o are deterministic values.

Let us consider the next parameter b. It is intersection point where the ellipse and time axis are meeting each other. Position of the point b on the time axis depends on realization of the function x. This, in turn, depends on exploitation conditions of hoist rope which consists of:

- properties of hoist rope obtained during its production,
- properties of hoist rope environment (temperature, humidity, corrosiom, etc.),
- exploitation manner (intensity of hoist rope usage, possible rope lubrication during its technical survey etc.).

Therefore the point b position is random which means that function x(t) is a random variable. Let us assume that the whole randomness in the course of the function x(t) is included in the parameter b (now $b \equiv B$, a new random variable).

Let us consider the possible distribution of B.

At first, it is a continuous, displaced random variable. (We reject the case when rope just after putting into service breaks; it is known that $x = x_o$ for $t = 0$ and the rope is properly selected). If we assume that the speed of wire breaks is in a possitive, significant correlation with the rope weakening then - in the light of investigation [6] - the probability density function can be of the following shape:

$$f_B(b) = \begin{cases} \lambda \exp\left[-\lambda (b-b_o)\right] , & \text{for } b \geqslant b_o \\ 0 & \text{elsewhere,} \end{cases} \qquad (2)$$

Fig.3.

Now, assuming $Y = B^{-2}$ we have [14]:

$$F_Y(y) = 1 - F_B(1/\sqrt{y}\,) = \exp\left[-\lambda\left(\frac{1}{\sqrt{y}} - b_o\right)\right] , \qquad \text{for } y > 0.$$

Moreover

$$V = x_o^2 - x_o^2\, t^2\, Y$$

and we have [14]:

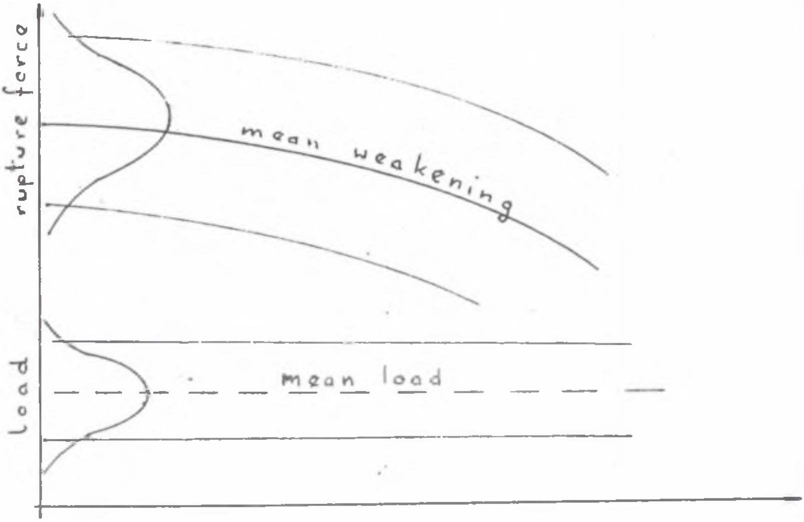

Fig. 1. Changes in distributions of breaking force and load for hoist ropes [12]

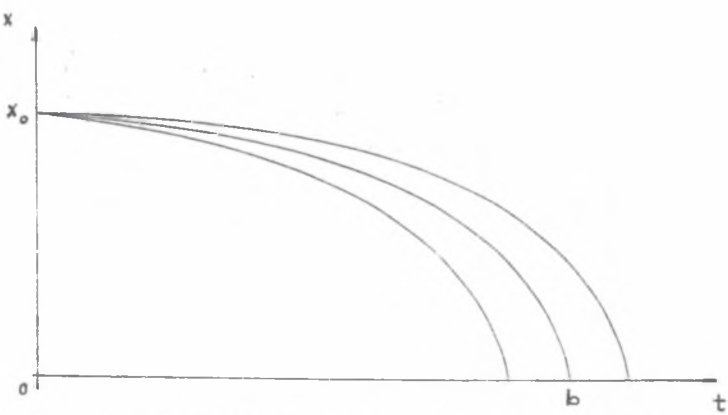

Fig. 2. Hoist rope tenacity mean value droppage in time

$$F_V(v) = 1 - F_Y\left(\frac{v-x_0^2}{-x_0^2t^2}\right) = 1 - \exp\left[-\lambda\left(\frac{x_0\,t}{\sqrt{x_0^2 - v}} - b\right)\right].$$

Finally, assuming $X=\sqrt{V}$ we obtain the formula for the distribution probability function

$$F_X(x;t) = 1 - \exp\left[-\lambda\left(\frac{x_0\,t}{\sqrt{x_0^2 - x^2}} - b_0\right)\right], \qquad \text{for } 0 < x < x_0 \qquad (3)$$

and the corresponding probability density function

$$f_X(x;t) = \frac{\lambda x_0\,x\,t}{(x_0^2 - x^2)^{3/2}} \exp\left[-\lambda\left(\frac{x_0\,t}{\sqrt{x_0^2 - x^2}} - b_0\right)\right], \quad \text{for } t \geqslant b_0, \qquad (4)$$

Fig.4, 5 for hoist rope tenacity X.

The above result is drastically different than that usually presented in the case of rope weakening consideration Fig.1 [12]. It is usually assumed that the distribution should be the normal one. In our case this distribution has been eliminated at the begining assuming that the new rope tenacity is known and its value is x_0. If this information is unknown the inception tenacity has in fact normal distribution. However, let us notice that even if the inception tenacity is known, the dispersion in the position of the point B is practically high. For unknown inception tenacity, the dispersion is very high reaching frequently several hundred per cent and our conclusions basing on it could be entirely useless for practice.

3. HOIST ROPE STRESS

For determination of the degree of hoist rope safety, a second basic information is needed: hoist rope stress. This magnitude is wanted in order to compare it with the rope tenacity. Both values create the system allowing to construct hoist rope safety measure.

Hoist rope stress understood as the surface force related to the unit of rope cross-section area, varies according to the phase of conveyance movement in shaft and depends on a load put into this conveyance. These values change many times (sometimes even several hundred) per day and one can assume it corresponds to oscillation. However, in order to make simple our consideration and making step towards safety, we can assume that the real rope load is constant, equals to the maximum countable load. Let us denote the inception rope stress by s_0. It relates to the new rope which metallic area is intact and maximal. During rope operation in shaft it is easy to notice that due to rope wearing process its metallic area diminishes and thus the real hoist rope stress increases. Let us assume that the real hoist rope stress during its operation fulfils the formula

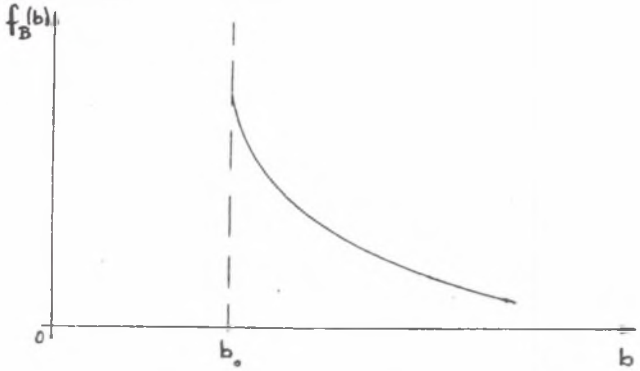

Fig. 3. Probability density function of the position of point b

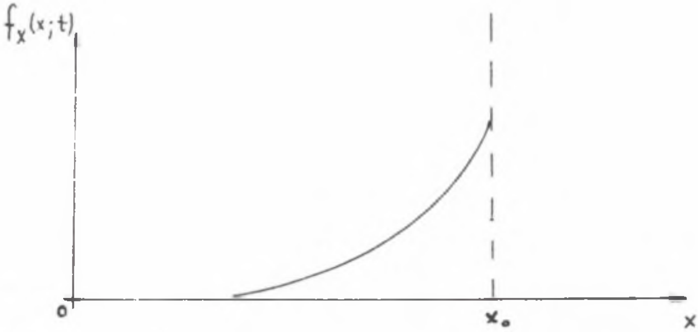

Fig. 4. Probability density function of hoist rope tenacity for a given moment of time

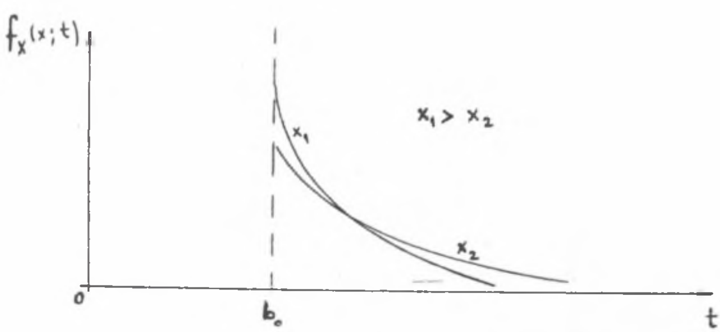

Fig. 5. Probability density functions of hoist rope tenacity vs time

$$S = s_o + \alpha t^{\beta} a^{\Omega} \; ; \quad t \geqslant 0, \quad \alpha > 0, \quad \beta > 1, \quad E(\Omega) = 0, \quad \text{Fig.6,} \tag{5}$$

where: α, β - structural parameters, deterministic variables,

a - constant, $a > 0$,

Ω - random variable; $\Omega : N(0, \sigma_{\Omega})$.

Let us notice that the whole randomness of the above formula is associated with the random variable Ω. Let us now determine the probability functions for random variable S.

We have

$$Z = a^{\Omega}, \tag{6}$$

and it has logarithmico-normal distribution with the probability density function

$$f_Z(z) = (z \sigma_{\Omega} \sqrt{2\pi})^{-1} \exp\left[-\frac{1}{2} \left(\frac{\lg z}{\sigma_{\Omega}} \right)^2 \right] \quad \text{for } z > 0. \tag{7}$$

If so the probability density function of rope stress is [14]:

$$f_S(s) = (\alpha t^{\beta})^{-1} f_Z \left(\frac{s - s_o}{\alpha t^{\beta}} \right) \quad \text{for } s > s_o, \quad t > 0, \text{ Fig.7.} \tag{8}$$

Practically, rope stress never exceeds rope inception tenacity x_o and thus

$$x_o > s_o + \alpha t^{\beta},$$

which gives

$$t < t_{max} = \left(\frac{x_o - s_o}{\alpha} \right)^{1/\beta}. \tag{9}$$

4. DEGREE OF HOIST ROPE SAFETY

Having determined rope tenacity running in time and rope stress course also in time we can try to consider degree of hoist rope safety.

We are now interested in the probability of an event that rope stress in a certain moment of time t overcomes rope tenacity, i.e.

$$P\{S \geqslant X\} = P\{S - X \geqslant 0\} = 1 - P\{S - X < 0\}. \tag{10}$$

The above indicates that the point of our interest is a certain random variable

$$W = S - X \tag{11}$$

for $0 \leqslant x \leqslant x_o$, $s_o \leqslant s \leqslant x_o$, $s_o - x_o \leqslant w \leqslant x_o$

which probable non-negative values should be considered.

Looking at the Fig.8 we can write down that the distribution function

$$F_W(w) = \int_0^{x_o} \int_{s_o}^{w+x} f_S(s) f_X(x) \, dx \, ds = P\{W \leqslant w\}. \tag{12}$$

Basing on it we can define

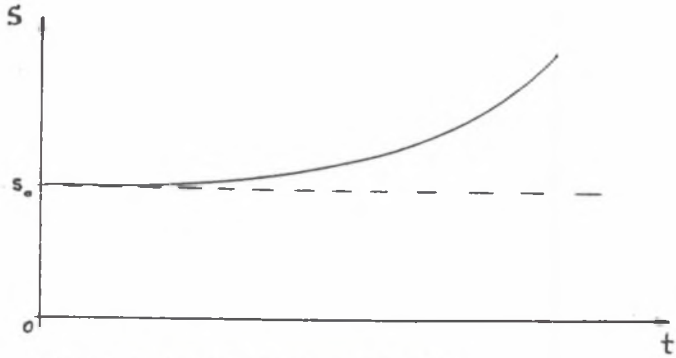

Fig. 6. Hoist rope stress in time

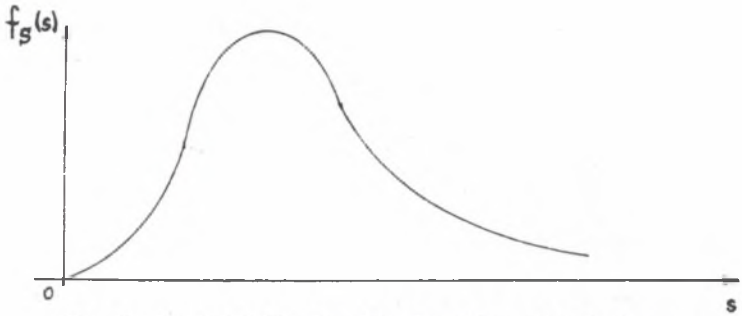

Fig. 7. Probability density function of hoist rope stress

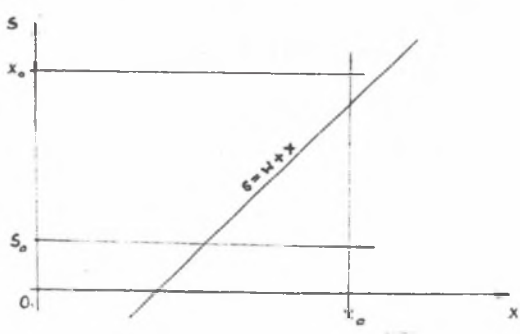

Fig. 8. Relationship between limits of hoist rope tenacity and stress

$$F_W(w=0) = P\left\{S \geqslant X\right\} = \int_0^{x_0} \int_{S_0}^{X} f_S(s)\ f_X(x)\ dx\ ds \qquad (13)$$

which is the degree of hoist rope safety wanted. Assuming now the appropriately low value of probability we can find time t in which our hoist rope should be withdrawn due to safety reason.

5. CONCLUDING REMARK

Presented model is only a trial of a construction of hoist rope safety measure free from the old-fashioned factor of safety which should die hardly as soon as only possible. This paper is addressed to the throng of professionalists dealing with rope problems on both empirical and theoretical fields. Some results presented here are purely theoretical. However, some results are based on mine data so they have practical advantage.

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Wpłynęło do Redakcji w listopadzie 1991 r.

PEWNE TEORETYCZNE ROZWAŻANIA O STOPNIU BEZPIECZEŃSTWA LIN NOŚNYCH

S t r e s z c z e n i e

Wartości współczynnika bezpieczeństwa lin nośnych urządzeń wyciągowych są obecnie weryfikowane w niektórych krajach. Artykuł rozważa problem miernika bezpieczeństwa lin rozumianego jako prawdopodobieństwo pojawienia się uszkodzenia katastroficznego - zerwania liny. Dwa podstawowe parametry liny są wzięte pod uwagę: wytrzymałość na zerwanie i naprężenia w linie. Otrzymano całkiem nowe wyniki, różne od tych, jakie są zwykle brane pod uwagę obecnie. W artykule przedstawiona jest formuła określenia stopnia bezpieczeństwa lin nośnych, co pozwala na obliczenie momentu, w którym lina powinna być wycofana z eksploatacji.

НЕКОТОРЫЕ ТЕОРЕТИЧЕСКИЕ РАССУЖДЕНИЯ О СТЕПЕНИ БЕЗОПАСНОСТИ НЕСУЩИХ ТРОСОВ

Р е з ю м е

Значения коэффициента безопасности несущих канатов подъемных машин в настоящее втемя проверены в некоторых странах . Статья касается проблемы измерителя безопасности канатов , которая понимается как вероятность появления катастрофического повреждения - разрыва каната . Рассматриваются два основных параметра канатов : выносливость на разрыв и напряжения в канате . Получены абсолютно новые результаты , отличающиеся от тех , которые обычно берутся во внимание в настоящее время . В статье представлена формула определения степени безопасности несущих канатов , что позволяет вычислить момент , при котором канат должен быть выведен из эксплуатации.