Increase in the Accuracy of Calculating Length of Horizontal Cable SCS in Civil Engineering

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Abstract. A modification of the method for calculating the horizontal cable consumption of SCS established at civil engineering facilities is proposed. The proposed procedure preserves the prototype simplicity and provides a 5 percent accuracy increase. The values of the achieved accuracy are justified, their compliance with the practice of real projects is proved. The method is brought to the level of the engineering algorithm and formalized in the form of 12/70 rule.

1. Introduction
The physical level of the information infrastructure of a modern building is in most cases realized on the basis of wire communication channels, for the formation of which a structured cable system (SCS) is used [1-3]. Given the large capital costs for its implementation, the design of the SCS should be carefully considered [4-8].

2. Problem
During the design of the SCS, the required components consumption is calculated, including the horizontal cable, which is the most expensive part of the final specification of the element base, Fig. 1. Typically, a statistical method, which was proposed by AT&T Inc., in the early 90s of the last century, is involved [9]. The essence of the method is that to calculate the consumption of this component of SCS, a two-point estimate of the mathematical expectation of the average length of an individual horizontal cable is used in the form

\[ L = \frac{(L_{\text{min}} + L_{\text{max}})}{2} k_h + X \]

where: \( L_{\text{min}} \) and \( L_{\text{max}} \) - the length of the horizontal cable of the nearest and the most remote user workstation, respectively; \( k_h = 10\% \) - technology reserve factor; \( X \)- reserve for carrying out of cable cutting (60 - 80 cm depending on the type of SCS).

Then, a number of deterministic operations are performed, taking into account the technologies of installation and the features of the factory packaging of the cable.

The disadvantage of the method is that in a number of cases it gives a big error. The aim of the proposed procedure is to increase the accuracy while maintaining the circuit and the simplicity of the calculation.
3. Scheme and Justification of the Proposed Method

During the design of the SCS, the required components consumption is calculated, including the horizontal cable, which is the most expensive part of the final specification of the element base, Figure 1. Typically, a statistical method, which was proposed by AT&T Inc., in the early 90s of the last century, is involved. The essence of the method is that to calculate the consumption of this component of SCS, a two-point estimate of the mathematical expectation of the average length of an individual horizontal cable is used in the form

\[ \hat{L} = 0.5 \times (L_{\text{min}} + L_{\text{max}}) \]

The processing of the data of realized projects showed that in real projects the horizontal cable length distribution is close to normal with an average of 40 m and a variation coefficient of 0.42. Simultaneously, it demonstrates a small positive asymmetry with a coefficient \( \gamma_3 = 0.25 \) and a negative excess with a coefficient \( \gamma_4 = -0.6 \). The excess does not affect the accuracy of the evaluation \( \hat{L} \) according to formula 1 and is not taken into account in further analysis. Asymmetry in some cases significantly distorts the estimate, and the estimated error increases with the scale of the project.

The reason for the error is that, due to \( \gamma_3 > 0 \) the average actual length of the cable is significantly different from the half-sum of the largest and smallest lengths \( L_{\text{min}} \) and \( L_{\text{max}} \).

This disadvantage can be eliminated without loss of simplicity of calculations due to the introduction of a special procedure for selecting the quantities \( L_{\text{min}} \) and \( L_{\text{max}} \).

During the analysis it is assumed that user workplaces are evenly distributed over the area of the territory served by a technical room; the location of technical rooms differs from the optimal (by the criterion of minimum \( \hat{L} \)) so that \( \gamma_3 = 0.25 \); routes for laying of horizontal cables are arranged identically.

Smallnesses \( \gamma_3 \) and \( \gamma_4 \) allow to use the method of moments and approximate the actually obtained function of the probability density of cable lengths by the Gram-Charlier series [10], which is a normal distribution with correction. To ensure generality of consideration, this distribution is conveniently written using a standardized chance variable: \( x = (t - Mt)/\sigma \)

\[ \phi_x(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} [1 + \frac{\gamma_3}{3!}(x^3 - 3x) + \frac{\gamma_4}{4!}(x^4 - 6x^2 + 3) + ...] \]  

Function of the form formula 2 in this case is inconvenient for the analysis. To eliminate this defect, we pass from the canonical form of the Gram-Charlier series to the distribution function \( \Phi_x(x) \) [11]:

\[ \Phi_x(x) = \int_{-\infty}^{x} \phi_x(t) dt \approx \Phi(x) + \varepsilon(x) + ... \]  

where: \( \Phi(x) \) – normal distribution function, \( \varepsilon(x) = \frac{\gamma_3}{3!(\sqrt{2\pi})^2} (1 - x^2)e^{-\frac{x^2}{2}} + \frac{\gamma_4}{4!(\sqrt{2\pi})^2} (3x - x^3)e^{-\frac{x^2}{2}} \) - the correction that takes into account the difference between the real distribution and the normal distribution.

With small differences in the distribution \( \phi_x(x) \) from the normal one, the right-hand side of the expression formula 3 can be represented by the Maclaurin series in powers of \( x \) [12]. This gives an estimate of the value of the mathematical expectation of a standardized chance variable

\[ x_0 = \frac{-\gamma_3}{3!(1 + 3\gamma_4 / 4!)} \]  

From the expression of formula 4 it follows that [13]

- in real projects for which \( \gamma_3 > 0 \) and \( (3\gamma_4/4!) < 1 \), we have \( x_0 < 0 \), that is, in the interval of the linear representation \( \varepsilon(x) \) formula 4 gives an estimate from below of the actual value of the mathematical expectation of the length of a single cable [14];
due to the smallness of the absolute values $\gamma_3$ and $\gamma_4$ the difference $x_0$ from zero in the indicated interval will not be significant.

The expression formula 4 does not allow for engineering calculations and therefore is of theoretical interest. This is due to the fact that the calculations require knowledge of the coefficients $\gamma_3$ and $\gamma_4$, the definition of which for a particular SCS is a separate independent task. In addition, this procedure can not in principle be carried out according to a two-point scheme [15].

The absolute values of the derivatives $\frac{dF_u}{d\gamma_3} = \frac{1-x^2}{3\sqrt{2\pi}} \exp(-\frac{x^2}{2})$ and $\frac{dF_u}{d\gamma_4} = \frac{3x-x^3}{4\sqrt{2\pi}} \exp(-\frac{x^2}{2})$ are small in the neighborhood of $x_0$. Differences from zero are further reduced in the neighborhood of the roots of the equations $\Phi_u(x) = \gamma$ and $\Phi_u(x) = 1-\gamma$, that is, for $x\neq0$ in case of sufficiently large quantities $\gamma$. This is determined by the presence of a cofactor $\exp(-x^2/2)$ in the expressions for their calculation and means a weak effect on the further presented results of those variations of the asymmetry and kurtosis coefficients that are observed in the SCS construction practice [16].

![Figure 1](image)

**Figure 1.** Relative cost of separate groups of SCS element base

In the process of designing SCS, it is advisable to use the natural symmetrical boundaries [$\gamma; 1-\gamma$] of the horizontal cable length distribution interval [17-19]. Then, under the condition of a simple and convenient two-point evaluation, the value $x_0^*$ is found as:

$$x_0^* = \frac{\Phi_u^{-1}(\gamma) + \Phi_u^{-1}(1-\gamma)}{2}$$

where through $\Phi_u^{-1}(\gamma)$, we denote the solution of equation $\Phi_u(x) = \gamma$.

Wherein $x_0^* \approx x_0$ ($x_0$ - the actual value of the average cable length).

The normal distribution function $\Phi(x)$ is mirror-symmetric: $\Phi(x) = 1-\Phi(-x)$ and has an inflection point at $x = 0$. Then at $x \approx x_0$ we can obtain an estimate of the derivative of the Gram-Charlier series correction in the following form $\frac{d\varepsilon(x)}{dx} = -\frac{3\gamma_4}{4!}$. Taking into account the fact that in the horizontal subsystem of the standard SCS project $\gamma_4<0$, we can state that for small values $|0,5-\gamma|$ the inequality $x_0^* < x_0$ is satisfied.

As $x$ increases, the modulus $\varepsilon(x)$ rapidly tends to zero due to the presence of a multiplier $\exp(-x^2/2)$ in each term of this function. Thus, when $\gamma \to 0$ we have already $x_0^* > x_0$. This means that there is at least one value of $x$, for which the error in determining $L$ of the form formula 5 is zero.

The results of calculations for formula 5, performed at typical values of the asymmetry and kurtosis coefficients, are shown in Figure 2. They indicate that, with average values of the coefficients $\gamma_3$ and $\gamma_4$ the minimum value of the calculation error $x_0^*$ is reached at $\gamma=18\%$. The use of such a border is
inconvenient for practical use because of the difficulty in counting of the total number of individual cables that correspond to the "allowed" interval of length variation. In order to eliminate this disadvantage in the estimate $L$ it is advisable to fix the interval boundaries on the basis of the probability value $\gamma = 5 \%$.

![Figure 2](image)

**Figure 2.** The effect of the parameter value $\gamma$ on the error value (percent) of determining the mathematical expectation $x_0$.

The transition to the interval $[0.05; 0.95]$ gives the following important advantages.

1. The boundary $1 - \gamma = 95 \%$ with the values of the distribution parameters characteristic for the horizontal subsystems of the SCS, corresponds to the expected value of the cable length of about 70 m. Exceeding this value in practically realizable projects is undesirable because of the rapid growth of capital costs for the creation of the SCS.

2. The boundary $5 \%$ for the distribution formula 1 corresponds to 12 m. This is approximately equal to the length of the cable to the nearest workplace outside the technical room, figure 3 and, as noted further, significantly simplifies the process of carrying out design works.

![Figure 3](image)

**Figure 3.** Histogram of distributions of the minimum distances to the first user workplace (mean of 11.8 m, standard deviation of 2.3 m)

When the parameter change interval $\gamma \in [0.005; 0.95]$ is selected, the error value is small and according to Figure 2 will be $\pm 2.5 \%$. The presence of a small positive error is useful, since it practically coincides with the normative 2% increase in cable consumption due to unevenness of its laying by hand, which can now not be taken into account separately.

4. **Estimating the Accuracy of the Method**
As an estimate of the degree increases the accuracy of the calculation, the variable is used

\[ k_p = \frac{1 + \text{abs}(x_1 - x_0)}{x_0} \]

\[ k_p = \frac{1 + \text{abs}(x_2 - x_0)}{x_0} \]  

(6)

where: \( x_1, x_2 \) - the design value of the average length of the cable according to the known and proposed method, respectively.

The results of the calculations are shown in figure 4 and show that:

- 75% of implemented cable systems perform at least one of two events: \( L_{\min} < 12 \text{ m} \) and \( L_{\max} > 70 \text{ m} \), i.e. the proposed method has a wide field of application;
- an integral increase in the accuracy of the cable length determination for the implemented projects is 4.8%;
- the proposed method allows in 30% of cases to increase the accuracy of determining the average length by 8% or more, that is, significantly reduce the probability of a coarse design error.

The error in determining the average length of a horizontal cable of 8% or more, which is observed in practice and according to statistics figure 4a appears on average in 13% of the implemented projects, can be explained by a violation of the condition of uniform distribution of working places. The same reason is due to those 11% of cable systems in which the proposed method gives a greater deviation from the actual value in comparison with its prototype.

![Figure 4](image)

**Figure 4.** Errors in calculating of the average lengths of horizontal cables: a) the absolute value of the error in determining the average value of the horizontal cable length; b) the magnitude of the decrease in the error in determining of the average length as a result of the proposed method application.

5. **Modification of the Algorithm for Calculating of Horizontal Cable Consumption**

The advantage of the proposed method is that the algorithm for estimating the average length of a horizontal cable does not undergo significant changes [20]. The most significant corrections are reduced to the following:

- estimating the average length of the horizontal cable SCS is calculated as the half-sum of the lengths of the maximum and minimum lengths of spans, provided that any of the values of this pair is not more than 70 m and not less than 12 m (formalized as a rule 12/70);
- the cable consumption for the formation of a 70 m long or more spans is determined separately by analogous rules;
- when determining the horizontal cable consumption, the spans of less than 12 m in length are not taken into account;

The latter one is determined by the fact that the average value of the horizontal cable remnant in the factory package, in case of the most popular in practice 1,000 feet ones turns out to be close to 30 m.
According to the expression of formula 3, the share of cables less than 12 m in length does not exceed 5%. From a practical point of view, this means that all those necessary cables of a small length can be taken from those scraps in the boxes that have remained there after laying long lines.

6. Conclusion
A method is proposed for calculating the horizontal cable consumption of the SCS, which:

- completely preserves the simplicity of its prototype and does not require an increase in computational costs in the course of works on the design of the SCS;
- provides a significant close to a 5 percent increase in the accuracy of finding the length of the horizontal cable;
- has a very wide field of application in practice;
- is formalized in the form of a simple and understandable rule 12/70.

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