

Safety parameters calibration in the structural design of sewer liners

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Abstract. The article concerns aspects of safety in the process of designing continuous polymer liners used to strengthen and seal sewers and drains. The issues of safety coefficients, the variability of basic load-bearing parameters of liners and the problem of sensitivity of analytical solutions describing load-bearing capacity are discussed. The currently used magnitude of safety factors has been verified. The results of an examination on the safety index of liners for strengthening sewers has been presented in the paper. The necessity for the verification of current concepts of liner safety normalisation was herein addressed. A postulation to abandon the analogy of liners for newly constructed pipes was formulated. Calculations using the Hasofer-Lind safety index (First Order Reliability Method) were performed in some cases. A verification and evaluation of the global safety factor for sewer liners were herein carried out.

1 Introduction

Reliability is now becoming the basic measure of long-term structural safety. In front of the decline of deterministic methods of estimating the load capacity of structures in favour of probabilistic and stochastic methods is observed. For many years, this tendency has been manifested by introducing the dimensioning of structural elements to modern algorithms through the use of various types of safety factors. Arbitrarily assumed safety measures are replaced by the resulting quantities from a probabilistic analysis of construction work.

The fact that the aspect of safety of lining reinforcing sanitary sewers was not fully examined, prompted the author to undertake a comprehensive analysis of the safety of this type of construction in the light of previous experience, laboratory tests and design algorithms. The rapid increase in the popularity of liner technology has made it so that the methods of their dimensioning were borrowed from the dimensioning algorithms of newly-installed underground pipes. However, the applied analogy turned out to be a false assumption and the need to develop new solutions arose. Over time, some methods of load capacity estimation departed from the assumptions of the analogy to installed pipes in excavations. However, the problem of liner safety has been transferred to new algorithms directly without a comprehensive examination of this aspect of new solutions. In order to ensure a reliable estimation of the load-bearing capacity of the lining constructions, it is

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therefore necessary to update existing algorithms with reliability aspects based on statistical data.

The current analysis is one of the first steps towards a more rational and safe dimensioning of the liners. The first step by the author was to estimate the so-called conventional global safety factor for the basic approach to the stability problem of liners [2]. The result of this analysis was the conclusion that the hitherto used safety factor values are too low for the high coefficients of variation of geometrical and mechanical parameters. This article presents the next step of a comprehensive reliability analysis based on the estimation of Hasofer-Lind reliability indexes using well-known basic load estimation algorithms and the results of laboratory tests carried out in various scientific centres [1, 10, 14].

The Hasofer-Lind reliability index is an advanced and verified measure of safety based on selected probabilistic parameters of the structure. The advantage of this size is that it is not necessary to recognize all the characteristics of random variables describing the safety of the structure. Only basic parameters such as average value and standard deviation are sufficient for the analysis. Due to the ignorance of the function of the probability distributions of geometrical and mechanical parameters of liners, the most commonly observed normal distribution was assumed. Average values and standard deviations of geometrical and mechanical parameters were taken from the results of laboratory tests.

2 Estimation of Hasofer-Lind index reliability

The analysis assumes that all parameters affecting the load-bearing capacity of liners apply to the normal distribution. The same assumption was assumed for the boundary function. In addition, it was assumed that random variables are independent.

The general definition of the probability of failure:

$$P_f = \Pr\{R < S\} = \Pr\{R - S < 0\} = \Pr\{R / S < 1\} \quad (1)$$

where: R - random variable representing strength and S - random variable representing the load.

Formulation of the limit function:

$$G(R, S) : (R - S) = 0 \quad (2)$$

Random variables are normalized to reduced variables by the following transformation:

$$u_i = \frac{x_i - \mu_i}{\sigma_i} \quad (3)$$

where: u_i - i -th normalized random variable, x_i - i -th random variable, μ_i - average value i -th random variable, σ_i - standard deviation of i -th random variable.

The basic formula describing the snap-through stability under the action of groundwater lining installed in the sanitary sewer is as follows [2]:

$$P_{cr} = E \cdot \left(\frac{t}{D} \right)^{2,2} \quad (4)$$

where: P_{cr} - critical peripheral ground water pressure, t - liner thickness, D - average diameter of the liner, E - long-term elastic modulus of the liner.

In the problem under consideration, the border function takes the following form:

$$G(E, t, D, p_w) = E \cdot \left(\frac{t}{D}\right)^{2,2} - p_w = 0 \tag{5}$$

where: p_w - groundwater pressure at the level of the channel kinetics.

The reduced variables have the form:

$$u_1 = \frac{E - \mu_E}{\sigma_E}, \quad u_2 = \frac{t - \mu_t}{\sigma_t}, \quad u_3 = \frac{D - \mu_D}{\sigma_D}, \quad u_4 = \frac{h_w - \mu_{p_w}}{\sigma_{p_w}} \tag{6}$$

where: u_i - normalized random variables, μ_E - average modulus of elasticity, σ_E - standard deviation of the elastic modulus, μ_t - average thickness of the liner, σ_t - standard deviation of liner thickness, μ_D - average diameter of the floor covering, σ_D - standard deviation of the floor covering diameter, μ_{p_w} - average ground water pressure, and σ_{p_w} - standard deviation of groundwater pressure.

We can substitute for the formula (5) the following values resulting from the transformation of normalized random variables:

$$E = \mu_E + u_1 \cdot \sigma_E, \quad t = \mu_t + u_2 \cdot \sigma_t, \quad D = \mu_D + u_3 \cdot \sigma_D, \quad h_w = \mu_{p_w} + u_4 \cdot \sigma_{p_w} \tag{7}$$

As a result, we get the following form of the limit function:

$$G(u_1, u_2, u_3, u_4) = (\mu_E + u_1 \cdot \sigma_E) \cdot \left(\frac{\mu_t + u_2 \cdot \sigma_t}{\mu_D + u_3 \cdot \sigma_D}\right)^{2,2} - (\mu_{p_w} + u_4 \cdot \sigma_{p_w}) = 0 \tag{8}$$

Determination of the Hasofer-Linda reliability index β comes to the solution of the following system of equations [8]:

$$u_i^* = -\gamma_i \cdot \beta \tag{9}$$

$$G(u^*) = 0 \tag{10}$$

where:

$$\gamma_i = \frac{\left[\frac{\partial G(u)}{\partial u_i}\right]_{u=u^*}}{\sqrt{\sum_{i=1}^{n=4} \left[\left(\frac{\partial G(u)}{\partial u_i}\right)^2\right]_{u=u^*}}} \tag{11}$$

The above system of equations is a problem of non-linear optimization and requires calculation with the use of iterative methods. As a result of the calculations, we obtain the minimum value of the reliability index occurring at the most unfavorable combination of random variables. The Hasofer-Lind reliability index allows determining the cumulative function of the construction safety function, on the basis of which the probability of failure

occurrence can be determined. The typical minimum value of the reliability index assumed in the calibration of standards is 4.26, which corresponds to the probability of failure at the level of $10e-5$. In cases of structures with a higher level of consequences of failures, the reliability index increases even to 5.2, which corresponds to the probability of a failure of $10e-7$. For typical structural engineering problems, the most frequently assumed reliability index is 4.26 [4]. An example of this may be recommendations [3].

The issue of the safety of floor coverings has not been investigated so far, and the level of safety factors in existing computational algorithms is adopted on the basis of an analogy to wires installed in the ground. In comparison to new sewer pipes, one should, however, expect a decrease in the level of reliability resulting from the greater variability of geometric and mechanical parameters and the lack of their control.

Table 1. Calculated Hasofer-Lind reliability indexes.

exam. prog./liner type	diameter D [mm]		wall thickness t [mm]		Modulus of elasticity E [MPa]		reliability index H-L for following water head level above invert			
	aver	std dev	aver	std dev	aver	std dev	2 m	3 m	4 m	5 m
Guice et al Inliner	303,45	0,73	7,00	0,48	2018,35	188,03	4,68	4,46	4,23	4,01
Guice et al Insituform Std.	303,11	0,31	5,98	0,25	3093,17	132,93	8,33	7,92	7,52	7,14
Guice et al Insituform Enh.	303,91	0,44	5,73	0,12	3713,66	195,98	7,96	7,66	7,37	7,07
Guice et al NuPipe	301,75	2,93	9,68	0,08	2650,70	154,72	8,17	8,04	7,92	7,80
Guice et al Paltem HL	303,28	0,00	6,44	0,02	2018,79	88,02	7,90	7,49	7,07	6,66
Guice et al KM Inliner	302,94	0,53	4,94	0,15	1948,52	184,80	3,49	3,10	2,72	2,34
Guice et al Superliner	303,28	0,67	5,86	0,13	12306,56	3367,31	1,79	1,77	1,76	1,76
Aggarwal et al Epoxy 250/99 P&S	251,64	0,89	5,27	1,57	2215,71	161,23	2,11	1,93	1,76	1,61
Aggarwal et al Poly 405	248,02	3,39	5,03	0,55	1800,50	389,28	2,00	1,86	1,72	1,58
Aggarwal et al Derakane	250,83	1,68	5,42	1,69	1458,83	162,11	1,80	1,60	1,41	1,24
Aggarwal et al 4168.00	250,24	0,85	6,62	2,24	2117,00	268,42	2,08	1,94	1,82	1,71
Aggarwal et al Synres	249,76	1,43	5,54	2,01	1569,17	348,85	1,96	1,42	1,26	1,12
Wagner 250	247,90	3,69	5,60	1,01	2690,09	529,96	2,36	2,27	2,18	2,09
Wagner 300	295,42	3,83	8,87	1,00	2863,63	195,11	6,25	6,03	5,82	5,61

In order to verify the level of security provided by the existing calculation algorithms, a number of calculations of reliability indicators were carried out. Statistical data describing the geometrical and mechanical parameters of the liners necessary to carry out the calculations were taken from the results of laboratory tests [1, 10, 14]. Characteristic levels of groundwater affecting the floor covering were assumed as for the most common, real design cases, i.e. 2, 3, 4, and 5 m above the channel kinetics. Calculations of the Hasofer-Lind reliability index were carried out for individual design issues. The results of calculations are presented in Table 1.

Analyzing the presented results, one can conclude that the reliability index is not directly determined by the average values of geometrical and mechanical parameters and their standard deviations are definitely greater. This aspect is not directly taken into account in any of the author's known load capacity estimation algorithms. A typical scheme for considering the safety of liner constructions is the unified global safety factor, which does not take into account the specificity of the material. The observed phenomenon is proof of the need to include partial safety coefficients for particular parameters in calculation algorithms.

The presented calculation results were performed for various existing laboratory tests results, they do not constitute a basis for comparing different material solutions in terms of their reliability. Different diameters and wall thicknesses of floor coverings were used. The results presented for individual solutions do not correspond together. However, the calculations carried out give a picture of the behavior of reliability indexes in the scope of the applicability of floor coverings.

Another conclusion is to be found when analyzing declines in the size of reliability indicators together with groundwater level increase (Figure 1). It is characteristic that this decrease takes place approximately linearly, but the gradient is variable for particular types of floor coverings. It can be concluded that if the linear decrease in the index would indicate the possibility of using a global safety factor in the computational algorithm, the variable gradient characteristic for the material makes the global safety factor not a universal factor of safety regulation.

3 Example of estimating the bearing capacity of a liner, taking into account the reliability aspect

To determine the significance of considering the reliability aspect in liner design, calculating the reliability index for a specific project task was carried out. The data used as part of the design workshops, which took place during the Underground Infrastructure Research conference [6, 12], were accepted. The case of canal reinforcement was considered there with a resin lining with imposed geometrical and mechanical parameters. The aim of the workshop was to determine the thickness of the liner ensuring construction safety by any method of load capacity estimation. A design example is shown in Fig. 2. The average thickness of the liner obtained from the calculations carried out with several methods was 14.5 mm, and the range of this size ranged from 10.7 to 22.0 mm.

Assumed parameters:

sewer diameter DN800

liner material: polyester resin

liner modulus of elasticity: short term 3000 N/mm², long term 1500 N/mm²

bending strength: long term 20 N/mm²

compressive strength: long term 40 N/mm²

Poisson's ratio: $\nu = 0,35$

ground modulus of elasticity $E_s = 10 \text{ MN/m}^2$

unit weight $\gamma = 19 \text{ kN/m}^3$

rate of compaction $D_{Pr.} = 90\%$

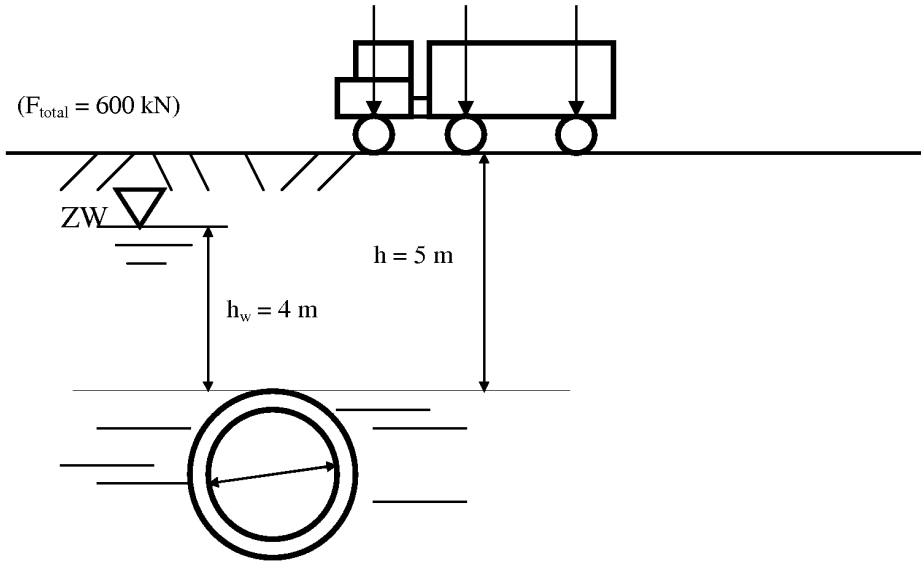


Fig. 1. Load configuration.

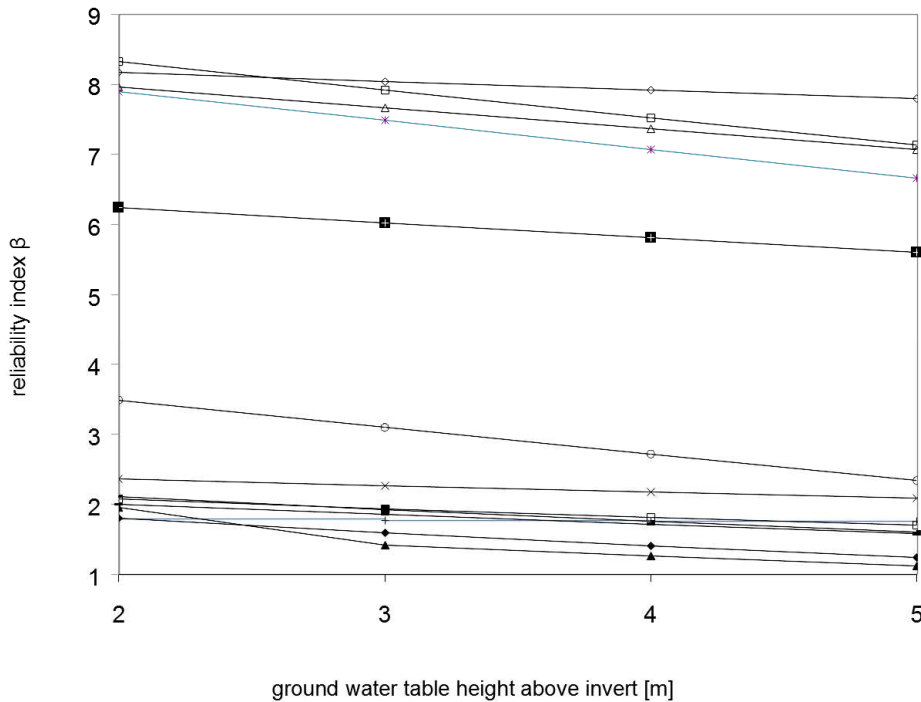


Fig. 2. Calculated Hasofer-Lind index vs ground water table height.

In the current analysis, an estimation of the necessary thickness of the liner was carried out including reliability by striving to achieve a reliability index of 4.26 corresponding to the minimum commonly accepted probability of failure. Statistical data describing random variables of diameter, wall thickness and the modulus of elasticity were estimated on the

basis of [8]. These data have been developed based on floor coverings made in real conditions. So you may think that they reflect the most reliable parameters. The following values of mean values and standard deviations were adopted: $\mu_E = 1500$ MPa, $\sigma_E = 300$ MPa, $\mu_D = 782$ mm, $\sigma_t = 1$ mm, $\sigma_D = 6$ mm, $\mu_{p_w} = 48$ kPa, $\sigma_{p_w} = 10$ kPa. The size of μ_t was variable and constituted an optimization parameter to achieve the appropriate reliability index.

From the performed calculations, $4.26 \mu_t = 18$ mm was obtained for the reliability index 4.26. This means that this value should be taken as the thickness of the lining ensuring the desired level of safety. The obtained quantity is significantly higher than the average calculated by classical analytical and numerical methods [6] [12]. On the basis of the performed calculations, the value of the global safety factor, which is defined for the Hasofer-Lind procedure as [4], was also estimated:

$$\gamma_s = \frac{S^* \cdot r_k}{r^* \cdot s_k} \quad (12)$$

where: γ_s - global safety factor, s^* - load size as the coordinate corresponding to the calculated reliability index, r_k - characteristic load capacity, s_k - characteristic load size.

The calculated values using the nominal values of the component parameters, i.e. the diameter of the liner $D = 800$ mm, the modulus of elasticity $E = 1500$ MPa, wall thickness $t = 18$ mm, groundwater pressure $p_w = 48$ kPa, were assumed to be characteristic values. The global safety factor calculated according to formula 12 was 2.89. It is a size significantly higher than that used in existing calculation algorithms. This confirms the thesis about the need to increase the safety factor previously set in [11].

4 SUMMARY

The article presents the basic results of the analysis of the safety of sewer liners. The size of reliability indexes associated with the selected real practical applications were estimated. The current security level implemented in existing load estimation algorithms for these structures has been examined. It has been suggested using far higher safety factors resulting from the high variability of geometric and mechanical parameters. Ultimately, it is advisable to move away from the concept of a global safety factor in favor of partial factors. This will allow a more rational and safer design of floor coverings. The obtained results show that existing load estimation algorithms require verification and recognition of reliability aspects. It is necessary to definitively abandon mechanical analogies for newly-installed wires. Research on the mechanical aspects of floor coverings indicates a completely different nature of the work of these structures. The use of such an analogy leads to a lowering of the level of safety, as evidenced by the current research.

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