ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Bridges and tunnels: theory, research, practice, 2025, № 28

UDC 625.745.2/.4-027.45

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ANALYSIS OF RELIABILITY MODELS FOR ROAD PIPE ELEMENTS DESIGNED IN ACCORDANCE WITH EUROCODE

Purpose. The main goal of the work is the analysis of reliability models for road pipe elements designed in accordance with Eurocode (EN 1990) through theoretical study. Additional objectives include: 1) theoretical study and overview of the retrospect of the development of reliability theory in construction; 2) revealing the reasons for the implementation of Eurocode as the world's first design system based on the principle of managed reliability; 3) detailed description of the three levels (formats) of reliability assessment proposed by the EN 1990 standard. **Methodology.** The research methodology is based on the theoretical study of reliability concepts, starting with the first probabilistic methods of the 1930s. 1. Analysis of Historical Basis: Examination of the structural safety concept by A. R. Rzhanitsyn (1952), known as the "second-moment method". In this approach, the generalized resistance (*R*) and the load (*E*) are considered as random uncorrelated variables. 2. Study of EN 1990 Reliability Formats: Analysis of the three levels of reliability assessment: – Level I (Semi-probabilistic method): Examination of the classical approach using partial safety factors (γ_k); – Level II (FORM): Analysis of the First-Order Reliability Method, which is the basic method for Eurocode; – Level III (SORM): Analysis of the "Exact procedure" of reliability theory, which involves analytical or numerical calculation of the probability of failure integral with arbitrary distribution functions. 3. Application to Road Pipes: Consideration of the practical application of these formats to road pipe elements, which are critically important engineering structures operating under a complex combination of permanent loads (soil embankment) and temporary loads (rolling stock). **Finding**. Managed Reliability: Eurocode is the world's first design system based on the principle of managed reliability. This principle provides the designer with tools for the quantitative assessment and modification of the reliability level. Basic Eurocode Method: It is justified that the First-Order Reliability Method (FORM), corresponding to Level II, is the basic method for Eurocode and has become a recognized tool for reliability management worldwide. Function of Reliability: The reliability concept in Eurocode ensures the safety of structures. It also serves as a criterion for project optimality and structural durability. Application to Road Pipes: – Level I is the primary approach for the routine design of road pipes; – Level II (FORM) is used for critical and large culverts. It allows for the quantitative assessment of the reliability index β and ensures that it exceeds the minimum acceptable level; – Level III (SORM) is practically not used in routine design but can be employed in scientific research or for unique objects to obtain the most accurate estimate of the probability of failure. **Originality.** It is argued that the concept of reliability ensures the safety of road pipes and provides the designer with tools for qualitative assessment and management of the level of reliability, serving the criterion of optimality of the design and durability. **Practical value.** Safety Management: The reliability concept embedded in Eurocode ensures the safety of buildings and structures. Optimization Tool: The main principle of managed reliability allows the designer to quantitatively assess and change the reliability level, serving not only as a measure of safety but also as a criterion for project optimality and structural durability. Relevance for Road Pipes: The application of the three-level system for reliability assessment is especially relevant for road pipe elements because it allows for accurately accounting for the complex influence of the soil embankment and traffic load, ensuring their optimality and durability.

Keywords: Eurocode; reliability; limit state method; managed reliability; road pipe

Introduction

The concept of reliability, which forms the basis of the Eurocodes (the method of partial safety factors), is rooted in the first attempts to apply probabilistic methods in construction. In the 1930s, the first efforts to define and regulate the reliability level of building structures emerged. Among the pioneers in this field, M. Mayer and N. F. Khotsialov are often mentioned.

Significant contributions to the development of reliability theory and probabilistic calculations were made by M. S. Strelletsky and A. R. Rzhanitsyn. Their work laid the foundation for understanding the probabilistic nature of loads and material strength. The development of the series of building standards named "Eurocodes" was initiated at an international level.

In the 1970s, the European Commission (then the European Economic Community) adopted a resolution on the need to harmonize building regulations in member countries. This was necessary to eliminate technical barriers to trade and ensure a uniform level of safety in construction. The Eurocodes began to be developed under the patronage of the European Commission as a set of unified technical rules.

In 1989, the responsibility for the development and publication of the Eurocodes was officially transferred to the European Committee for Standardization (CEN – Comité Européen de Normalisation). It is CEN that manages the process of creation, updating, and publication of all parts of the Eurocodes. Thus, the Concept of Reliability (limit state method) originated in scientific circles in the first half of the 20th century, and the Eurocodes, as a set of documents embodying this concept, were created at the initiative of the European Commission and developed by the European Committee for Standardization (CEN).

In Ukraine, the Eurocodes were implemented as national standards (DSTU-N B EN, 2008). Since July 1, 2014, the Eurocodes have been in force in Ukraine in accordance with a Resolution of the Cabinet of Ministers. The main document introducing the concept of reliability in Ukraine is DSTU-N B EN 1990:2008 "Eurocode. Basis of structural design".

The article by A. I. Lantukh-Liashenko (Лантух-Лященко, 2014) contains an analysis of the reliability models of elements designed according to Eurocode (EN 1990). The author highlights the retrospect of the development of reliability theory in construction, reveals the reasons for the implementation of Eurocode, and details its reliability concept, particularly the formats for reliability assessment.

The global goal of the work is the analysis of reliability models of elements designed in accordance with Eurocode, using theoretical research (CIRIA, 1977; Schneider, 1994; 1997).

The presented article is devoted to the analysis of reliability models of elements designed according to Eurocode (EN 1990). The global goal of the work is the analysis of reliability models of elements designed in accordance with Eurocode, using theoretical research. Special attention is paid to the elements of road pipes, which are critically important engineering structures operating under a complex combination of permanent loads from the soil embankment and temporary loads from rolling stock.

Purpose

The main goal of the work is the analysis of reliability models for road pipe elements designed in accordance with Eurocode (EN 1990) through theoretical study. Additional objectives include: 1) theoretical study and overview of the retrospect of the development of reliability theory in construction; 2) revealing the reasons for the implementation of Eurocode as the world's first design system based on the principle of managed reliability; 3) detailed description of the three levels (formats) of reliability assessment proposed by the EN 1990 standard.

Methodology

The key scientific ideas underlying the basis of modern reliability theory are: the statistical nature of the strength characteristics of the structure and its load parameters, the proven necessity of a probabilistic assessment of the structure's serviceability, the foundations of the limit state method, and the concept of structural safety by A.R. Rzhanitsyn (1952), which is the foundation of reliability theory, formulated as a probabilistic solution to the problem $G = R - E$. In this concept, the generalized resistance of the element (R) and the load (E) are considered as random uncorrelated variables with a normal distribution.

The safety characteristic β (the reliability index in Eurocode terminology) was defined as:

$$\beta = \mu_G / \sigma_G,$$

where μ_G and σ_G – are the first moments of the distribution (mathematical expectation and standard deviation) of the safety margin G. The probability of failure p_f was determined as

$$p_f = \Phi(-\beta),$$

where Φ – is the standard normal distribution function. This approach later became known in Western literature as the "second-moment method" and became the basis for designing structures for a specified reliability.

In the 1950s and early 1960s, reliability theory experienced rapid development, using the principles of probability theory, mathematical statistics, and the theory of random functions.

Three interconnected scientific ideas formed the basis of the new direction:

- external actions on the structure and its behavior during operation are random processes evolving over time;
- reliability is identified with the probability of parameters being within the acceptable region; exceeding this boundary is interpreted as a failure;
- structural failure is a consequence of the gradual accumulation of damage.

These principles were embodied in the fundamental research of V. V. Bolotin (1960s-1970s). In Western literature, the beginning of this period is associated with the work of C. A. Cornell in 1969. In it, the central idea of A. R. Rzhanitsyn's structural safety concept was presented with broad generalizations, and the safety characteristic received an elegant geometric interpretation as the shortest distance from the origin to the design point on the distribution density contour curve. The further development of the method led to the concept of determining the safety characteristic in the most general case (arbitrary distribution function and nonlinear limit state function) (Hasofer, 1974; Stewart, & Melchers, 1997; Faber, & Sørensen, 2003).

Eurocode is a package of European regulatory documents for the design of construction objects (EN 1990:2002), the implementation of which is part of Ukraine's state policy of integration with the European Union.

The fundamental novelty of Eurocode is recognized by world experts as the newest and most sophisticated basis for regulatory control in construction. It is the world's first design system based on the principle of managed reliability and durability. Unlike previous standards, which had "hidden" reliability, Eurocode has an apparatus for "managed" reliability, allowing the designer to manage the reliability of the object during the design process. The reliability level is checked using a quantitative indicator and can be changed upon the request of the client or the competent authority.

In EN 1990, the concept of "reliability" is defined as: "The ability of a structure or its element to perform specified functions throughout its design working life. Reliability is usually expressed in probabilistic terms". Reliability includes: safety, serviceability, and durability of the structure. Reliability, in addition to its main function of characterizing the safety level of the structure, also serves as a tool for optimizing project quality. The numerical parameter of reliability is the probability that the limit state will not be exceeded (P), and the probability that complements P to 1 is treated as failure (p_f).

Eurocode offers the user three levels (formats) of reliability assessment at the design stage.

1. Level I – Semi-probabilistic method

This is the classical approach, in which partial safety factors γ_k are specified within the regulatory document. The calculations are deterministic and do not require the designer to perform any probabilistic calculations. All necessary calculations within the framework of probability theory have been performed by the standard developers. Project reliability requirements are formulated as satisfying the inequality of the form:

$$E(F_k, \gamma_k) \le R(\alpha_k, f_k, \gamma_k),$$

where E – is the generalized external action; R – is the generalized resistance of the element; F_k, α_k, f_k, – are the characteristic values of external actions, geometric parameters, and mechanical characteristics of materials; γ_k – are the partial safety factors.

2. Level II – First-Order Reliability Method (FORM)

This is an analytical procedure of reliability theory, based on the assumptions of A.R. Rzhanitsyn and is the basic method for Eurocode. It requires probabilistic calculations from the designer. The method is based on the integral probability of failure of two random variables (resistance R and load E) assuming they have a normal distribution and are mutually uncorrelated. The safety condition is formulated as solving the problem $G=R-E$. The safety characteristic β (reliability index in Eurocode terminology) is

determined by the classical formula, in the case of normal distribution:

$$\beta = \frac{\mu_G}{\sigma_G} = \frac{\mu_R - \mu_E}{\sqrt{\sigma^2 R + \sigma^2 E}},$$

where μ і σ – are the mean values and standard deviations.

A graphical interpretation of the safety characteristic in the space of generalized variables E, R and failure probabilities p_R, p_E is shown in (Fig 1). Fig 2 again shows a graphical interpretation of the safety characteristic in the plane of dimensionless variables E/σ_E, R/σ_R.

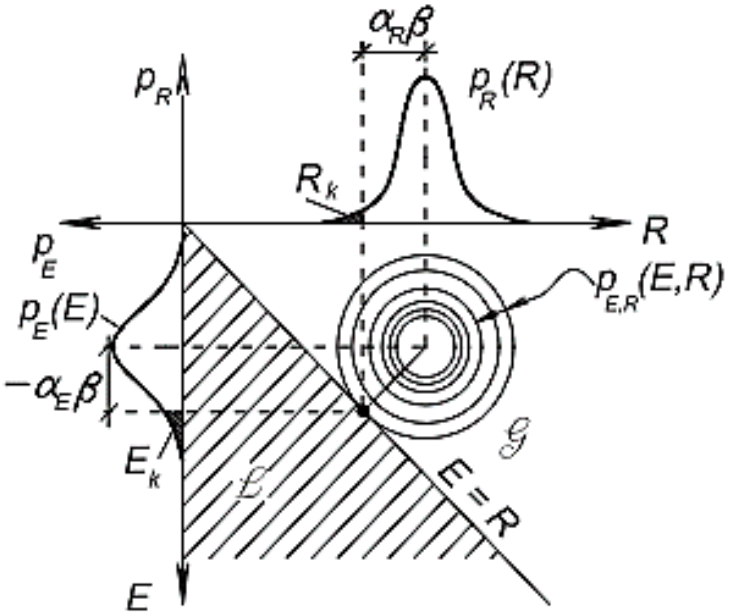

Fig. 1. Safety characteristics β

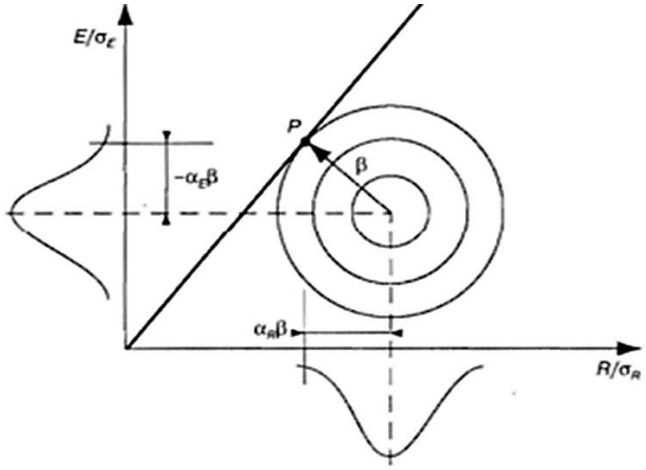

Fig. 2. Safety characteristic in the plane of dimensionless variables

The design (calculated) values of external action (E_d) and resistance (R_d) are determined so that the probability of obtaining a more unfavorable value is:

$$P(E>E_d)=\Phi(\alpha_E, \beta),$$

$$P(R>R_d)=\Phi(\alpha_R, \beta),$$

where α – is the sensitivity coefficient of the FORM method.

The minimum acceptable levels of the safety characteristic β for the three types of limit states are specified in EN 1990 (for example, for the ultimate limit state for 50 years β =3.8).

3. Level III – Exact procedure of reliability theory (SORM)

This is an exact procedure of reliability theory, based on the analytical or numerical calculation of the probability of failure integral with arbitrary distribution functions of load and resistance. Eurocode does not provide detailed recommendations, limiting itself to the definition of "exact methods".

Findings

The reliability concept embedded in EN 1990 is universal and applies to all types of structural elements, including road pipe elements. These are engineering structures laid under a road embankment that provide water drainage. The reliability of a road pipe is determined by its ability to withstand high external forces (E) from the soil embankment and moving load, as well as its resistance (R) to bending, compression, and loss of stability.

Application of Level I (Semi-probabilistic method). This is the main approach for routine design of road pipes. The engineer checks the condition:

$$E(F_k, \gamma_k) \leq R(\alpha_k, f_k, \gamma_k).$$

External actions F_k (soil weight, traffic load) are adjusted by partial safety factors γ_k.

Application of Level II (FORM). Used for critical and large culverts, as well as when flexible structures (corrugated metal, polymers) are used, where the interaction with the soil is critical. Since the limit state of the road pipe $G=R-E$ depends on random variables, the FORM method allows for the quantitative assessment of the reliability index β and ensures that it exceeds the minimum acceptable level established by EN 1990.

Level III (SORM). This level is practically not used in routine design of road pipes, but can be employed in scientific research or in the design of extremely unique and critical objects to obtain the most accurate estimate of the probability of failure.

Originality and practical value

It is argued that the concept of reliability ensures the safety of road pipes and provides the designer with tools for qualitative assessment and management of the level of reliability, serving the criterion of optimality of the design and durability.

Practical value. Safety Management: The reliability concept embedded in Eurocode ensures the safety of buildings and structures. Optimization Tool: The main principle of managed reliability allows the designer to quantitatively assess and change the reliability level, serving not only as a measure of safety but also as a criterion for project optimality and structural durability. Relevance for Road Pipes: The application of the three-level system for reliability assessment is especially relevant for road pipe elements because it allows for accurately accounting for the complex influence of the soil embankment and traffic load, ensuring their optimality and durability.

Conclusions

The concept of reliability in Eurocode ensures the safety of buildings and structures. The main principle of this concept is **managed reliability**, which provides the designer with the tools for quantitative assessment and modification of the reliability level. The First-Order Reliability Method (FORM), which is the basic method for Eurocode (Level II), has become a recognized tool for reliability management worldwide. The application of the three-level system for reliability assessment is especially relevant for road pipe elements, as it allows for accurately accounting for the complex influence of the soil embankment and traffic load, ensuring the optimality and durability of these critically important engineering structures. The concept of reliability in Eurocode is not only a measure of safety but also a criterion for project optimality and structural durability.

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АНАЛІЗ МОДЕЛЕЙ НАДІЙНОСТІ ЕЛЕМЕНТІВ ДОРОЖНІХ ТРУБ, ЩО ПРОЄКТУЮТЬСЯ У ВІДПОВІДНОСТІ ДО ЄВРОКОДУ

Мета. Головна мета роботи – аналіз моделей надійності елементів дорожніх труб, що проєктуються відповідно до Єврокоду (EN 1990), шляхом теоретичного дослідження. Додаткові завдання включають: 1) теоретичне дослідження та огляд ретроспективи розвитку теорії надійності у будівництві; 2) розкриття причин впровадження Єврокоду як першої у світі системи проєктування, що базується на принципі керованої надійності; 3) детальний опис трьох рівнів (форматів) оцінки надійності, що пропонуються стандартом EN 1990. **Методика.** Методика дослідження базується на теоретичному вивченні концепцій надійності, починаючи з перших імовірнісних методів 1930-х років. 1. Аналіз історичної основи: Вивчення концепції структурної безпеки А. Р. Ржаніцина (1952 р.), відомої як «метод другого моменту». У цьому підході опір елемента (R) та навантаження (E) розглядаються як випадкові некорельовані змінні. 2. Вивчення форматів надійності EN 1990: Аналіз трьох рівнів оцінки надійності: – Рівень I (Напівімовірнісний метод): Вивчення класичного підходу, де використовуються часткові коефіцієнти надійності. (γ_k); – Рівень II (FORM): Аналіз Методу першого порядку оцінки надійності, який є базовим методом для Єврокоду; – Рівень III (SORM): Аналіз «Точної процедури» теорії надійності, що передбачає аналітичний або чисельний розрахунок інтеграла ймовірності відмови з довільними функціями розподілу. 3. Застосування до дорожніх труб: Розгляд практичного застосування цих форматів до елементів дорожніх труб, які є критично важливими інженерними спорудами, що працюють під складним поєднанням постійних навантажень (ґрунтовий насип) та тимчасових навантажень (рухомий склад). **Результати.** Керована надійність: Єврокод є першою у світі системою проєктування, заснованою на принципі керованої надійності. Цей принцип надає проєктувальнику інструментарій для кількісної оцінки та модифікації рівня надійності. Базовий метод Єврокоду: Обґрунтовано, що Метод першого порядку оцінки надійності (FORM), який відповідає Рівню II, є базовим методом для Єврокоду і став визнаним інструментом управління надійністю в усьому світі. Функція надійності: Концепція надійності в Єврокоді забезпечує безпеку споруд. Вона також слугує критерієм оптимальності проєкту та структурної довговічності. Застосування до дорожніх труб: – Рівень I є основним підходом для рутинного проєктування дорожніх труб; – Рівень II (FORM) використовується для критичних та великих труб. Він дозволяє кількісно оцінити індекс надійності (β) та забезпечити його відповідність мінімально допустимому рівню; – Рівень III (SORM) практично не використовується в рутинному проєктуванні, але може бути застосований для унікальних об’єктів або в наукових дослідженнях для отримання найточнішої оцінки ймовірності відмови. **Наукова новизна.** Обґрунтовується, що концепція надійності забезпечує безпеку дорожніх труб та надає проєктувальнику інструментарій для кількісної оцінки та керування рівнем надійності, слугуючи критерієм оптимальності проєкту та довговічності. **Практична значимість.** Управління безпекою: Концепція надійності в Єврокоді забезпечує безпеку будівель і споруд. Інструмент оптимізації: Основний принцип керованої надійності дозволяє проєктувальнику кількісно оцінювати та змінювати рівень надійності, що є не лише мірою безпеки, але й критерієм оптимальності проєкту та довговічності споруди. Актуальність для дорожніх труб: Застосування трирівневої системи

оцінки надійності є особливо актуальним для елементів дорожніх труб, оскільки дозволяє точно врахувати складний вплив ґрунтового насипу та транспортного навантаження, забезпечуючи їхню оптимальність і довговічність.

Ключові слова: Єврокод; надійність; метод граничних станів; керована надійність; дорожні труби

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Надійшла до редколегії 01.10.2025.
Прийнята до друку 02.12.2025.