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PRINCIPLES OF CALCULATION AND MONITORING OF STRESS-STRAIN STATE OF THE GRADE-SEPARATED TRAFFIC INTERCHANGES IN MINSK

The results of scientific accompaniment and monitoring of construction of the transport interchange at the intersection of Independence Avenue and Filimonova Street over tunnels and other structures of Minsk subway. In order to ensure (in three shifts) the construction and installation works at construction of transport interchange around a number of innovative technologies in both for designing and work performance has been used. Construction monitoring envisaged continuous control of deformations and stresses of constructions of underground tunnels in the online mode and data transmission to all interested organizations. The calculation model of the existing tunnels has been developed, which includes the design of the lining and the surrounding soil massif. A theory for calculating underground structures based on the deformation of materials of building structures and geomechanical models composing a soil massif has been proposed.

Keywords: *transport structure, stress-strain state, traffic intersection, subway tunnel*

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ПРИНЦИПИ РОЗРАХУНКУ ТА МОНІТОРИНГУ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ТРАНСПОРТНИХ РОЗВ'ЯЗОКУ МІНСЬКУ

Подано результати робіт з наукового супроводження та моніторингу будівництва транспортної розв'язки на перетині пр. Незалежності з вул. Філімонова над перегінними тунелями та іншими спорудами Мінського метрополітену. Для забезпечення цілодобового (в три зміни) виконання будівельно-монтажних робіт при будівництві транспортної розв'язки використано ряд інноваційних технологій як для проектування, так і для безпосереднього виконання робіт. Моніторінг будівництва передбачав безперервний контроль деформацій і напружень конструкцій перегінних тунелів метрополітену в режимі онлайн і передачу даних всім зацікавленим організаціям. Розроблено розрахункову модель перегінних тунелів, що включає в себе конструкцію оздоблення та її навколишній ґрунтовий масив. Запропоновано теорію розрахунку підземних споруд на основі деформаційної моделі з застосуванням діаграм деформування матеріалів будівельних конструкцій і геомеханічних моделей складових ґрунтовий масив.

Ключові слова: *транспортна структура, напружено-деформований стан, перетин доріг, тунель метро.*

Introduction. Construction of a traffic junction at the intersection of Nezavisimosti Avenue with Filimonova Street was carried out over operated tunnels and other facilities of the Minsk subway.

The section of the tunnels in question is located on the first line of the Minsk metro between the Moskovskaya and Vostok stations and was put into operation on 26.12.1986. The project envisaged the construction of an overpass tunnels with typical prefabricated ferroconcrete spans for road bridges 24 m long and 21 m.

Initial data was provided by proposals for constructive and technological solutions for the traffic interchange at the intersection of Nezavisimosti Ave. with Filimonova street institutes «Minskinzhproekt» and «Minskmetroproekt».

Analysis of the latest sources of research and publications. Normative documents on the design of building structures underwent constant changes and additions and were often reprinted. The normative document SNiP 2.05.03-84 * «Bridges and pipes» [1] that operated until 2010 in the Republic of Belarus did not reflect the achievements of science and modern trends in the field of structural design.

The traditional approach to the construction of unique structures that have no analogues in underground construction is not always acceptable. Therefore, scientific research methods using innovative equipment and software complexes are of great importance [3–15].

Allocation of unresolved parts of a common problem. In recent years, the weight parameters of vehicles, the strength characteristics of concrete have increased, the industry has mastered the production of new efficient types of steels.

In 2002, in the Republic of Belarus, national standards for the design of concrete structures of the SNB 5.03.01-02 [2], harmonized with the Eurocodes (Eurocodes) [3.5] were put into effect.

Formulation of the problem. The development of unified European standards for the design of building structures – the Eurocodes, is aimed at «... ensuring the free movement between states of products, materials, technologies, services and scientific thought in the field of construction».

The Republic of Belarus also participates in this international program.

Structural and technological solutions. Initially, over the tunnels of the subway, a 200-meter overpass was designed at the base, which was intended for the installation of a monolithic reinforced concrete distribution plate.

The original version with a 200-meter overpass due to its high cost was rejected, after which other design solutions with a shorter length of overpass were considered. The final version of the decoupling assumed the construction of a 45-meter overpass, and access roads to it were carried out in the form of a mound.

The above-ground building structures of the multilevel transport crossing were above the operated tunnels of the first line of the Minsk Subway.

The adopted space-planning decisions required a change in the planning marks and the removal of soil over the tunnels of the subway, which led to a change in the initial stressed-deformable state of the underground structures on the site in question.

Metropolitan was put a criterion about the inadmissibility of moving the head of the rail more than 10mm. This criterion provided for the execution of construction and installation works in the «night windows». This circumstance would lead to an increase in the timing and cost of construction.

To carry out construction and assembly work in a short time and ensure the work in three shifts in the production of construction and installation works, a number of innovative technologies are applied.

Unique underground structures constructed in difficult engineering-geological conditions represent a special class of building structures. Unlike conventional building structures that are designed for specified loads, the design of the lining and the surrounding soil mass should be considered as a single system when calculating the limes operating in the regime of interacting deformations with the soil massif.

The calculation scheme of the system «lining – soil massif» is represented as a medium, divided into finite elements, which are joined together by rigid or elastic bonds.

The half-space under consideration is divided into three-dimensional elements. Since the complexity of such a calculation increases significantly, it is required for its implementation the use of software complexes specifically designed for the design of bridge and tunnel structures.

The finite element method allows calculating the lining not only on the basis of an elastic model of their interaction with the array, but also taking into account the nonlinearity of the deformation of the array and the lining. In this case, the geomechanical model of the soil massif corresponding to the engineering and geological conditions of the structure is taken into account, taking into account its anisotropy, heterogeneity, stratification, nonlinear nature of the soil operation and lining.

The finite element method makes it possible to calculate the design of the transport interchange at various stages of their construction in accordance with the technological sequence of opening the workings and erecting the object. Step-by-step disclosure of excavations is simulated in the design scheme by successive removal of the corresponding finite elements.

As a result of the decision, efforts, strains and deformations in the elements are obtained. The software complex used to solve this problem provides for the derivation of this information in a simple and visual form in the form of pictures of the distribution of stresses and deformations.

In this paper, using the integrated software package, an assessment was made of the effect of the constructed transport interchange complex on the existing structures of the Minsk subway tunnels.

Figure 1 – General view of multilevel transport interchange

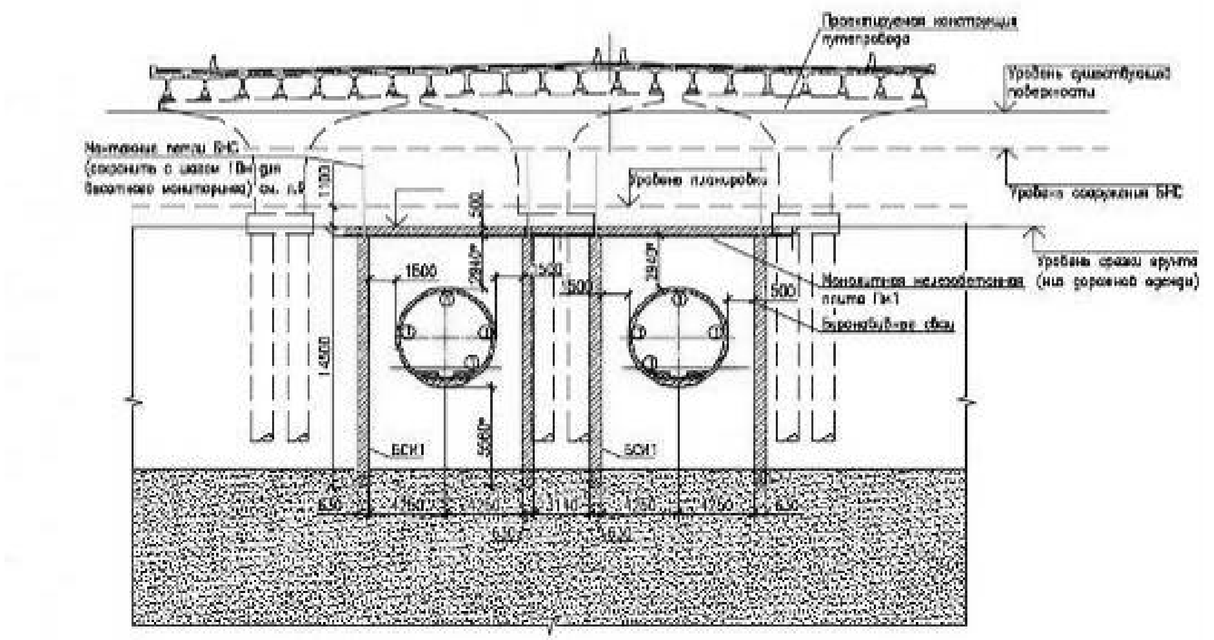

Figure 2 – Cross section of a multilevel transport interchange

The Republican Unitary Enterprise «Belarusian Road Research Institute BeldorNII» together with the «Bridges and tunnels»department of BNTU developed technical codes of established practice (TKP) and national annexes to them on the design of transport facilities identical to the design standards of the European Union: TKP EN 1991-2 , TKP EN 1992-2: TKP EN 1993-2 and TCKP EN 1994-2.

The National Standard implementing the relevant Eurocode includes the full text of the Eurocode as issued by the CEN, preceded by the National Title Page and the National Foreword, and which is accompanied by the National Annex.

The National Annex contains information on only those parameters that were left undefined in the Eurocode and are subject to national choice and are intended for use in the design of transport facilities to be built in the Republic of Belarus.

Calculations of structures for load capacity (1 group of limit states) and suitability for normal operation (2 group of limit states) in normal sections for any form of cross-sections with any damages, any arrangement of reinforcement within the cross-section and an arbitrary system of forces is made on the basis of a general deformation model section, which is based on the following assumptions:

– longitudinal deformations of concrete and reinforcement in normal sections are distributed according to the single-plane law at all loading levels;

– complete diagrams of uniaxial deformation are used for compressing and stretching concrete and reinforcement, including descending branches;

– sections can have any shape (rectangle, Taurus, I-beam, channel, circle, ring, triangle);

– sections are given in a discrete form by a combination of elementary sections of concrete and reinforcement; geometry, size and number of them are determined by the concrete situation;

– the stresses in concrete and reinforcement, as well as the deformations corresponding to them, are distributed evenly within the limits of elementary areas;

– the relative deformations of the reinforcement having adhesion to concrete are assumed to be the same as for surrounding concrete;

– sections may include concretes and reinforcement of different classes;

– equilibrium equations for external and internal forces are recorded in a uniform form under various force effects at all loading levels without seeking the position of the neutral axis.

The peculiarity of the new generation normative document for the design of bridge structures and pipes is the introduction of a unified approach to the calculation of sections of building structures from various materials.

At the present time, a lot of computer programs have been developed that use the «deformation model» to calculate normal cross sections, which allow calculations of arbitrary cross sections from any material, including multiply connected and non uniform ones.

For deformation of inhomogeneous elastoplastic soil models, deformation diagrams are given, as for metal and concrete.

Materials deformation diagrams are shown in Figures 3 – 5.

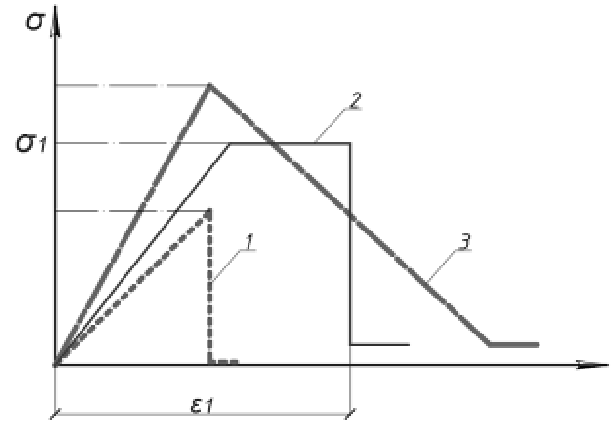

Figure 3 – Diagram of deformation of inhomogeneous elastoplastic soil models that take into account the fracture:
1 – brittle; 2 – elastoplastic; 3 – with a linear decrease in resistance beyond the ultimate strength [7]

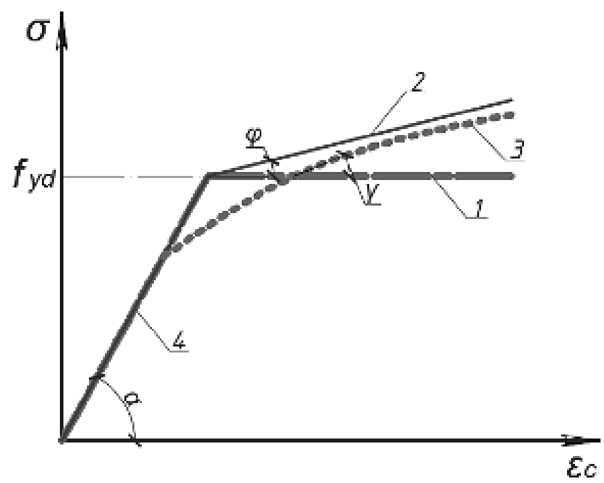

Figure 4 – Idealized steel deformation diagrams:
1 – Prandtl; 2 – with linear hardening; 3 – with nonlinear hardening; 4 – perfectly elastic

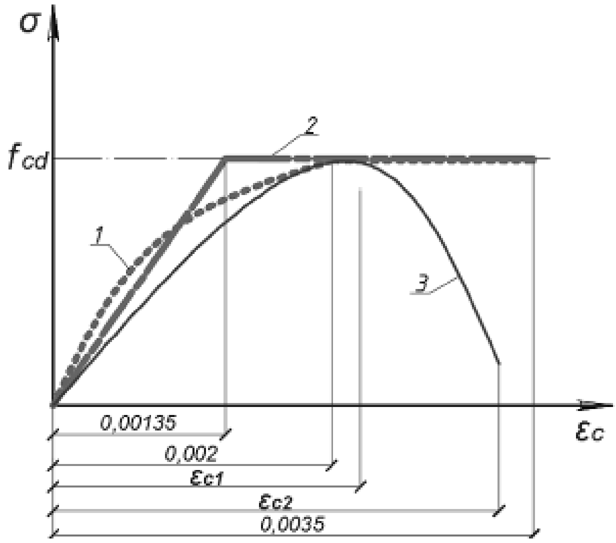

Figure 5 – Diagrams of concrete deformation during compression:
1 – parabolic; 2 – elastoplastic; 3 – nonlinear

To determine stresses and deformations in the cross-section of the elements, an iterative procedure is used, which makes it possible to follow the development of zones of plastic deformations and establish the limiting state by the criterion of limited plastic deformations for a metal and the criterion of limited limiting deformation for concrete.

Experience in the operation of building structures of transport interchange shows that their reliability and durability depend on a large number of random factors that vary with time [6].

The development of a method for calculating reinforced concrete structures with time factor is a further development of the method of calculating structures by limiting states.

In calculating the strength of sections normal to the longitudinal axis of the precast monolithic reinforced concrete element, use:

– equations of equilibrium of moments and longitudinal forces;

– equations of the distribution of relative longitudinal deformations within the compound section.

For the general case of calculating the section of a precast-monolithic element, the equilibrium condition in the matrix form

$$\begin{Bmatrix} N_{Sd,z} \\ M_{Sd,x} \\ M_{Sd,y} \end{Bmatrix} = \begin{bmatrix} R_{1,1} & R_{1,2} & R_{1,3} \\ R_{2,1} & R_{2,2} & R_{2,3} \\ R_{3,1} & R_{3,2} & R_{3,3} \end{bmatrix} \begin{Bmatrix} \varepsilon_z \\ k_x \\ k_y \end{Bmatrix}, \qquad 1)$$

where εz – longitudinal relative deformation at the level of the selected longitudinal axis z;

kx, ky – changes in the curvatures in planes coinciding with the x and y axes;

R1,1 – R3,3 – elements of the matrix of instant stiffnesses for the composite section.

The introduction into the normative documents of deformation diagrams connecting the stresses and deformations of materials in the process of loading made it possible to significantly improve the methods for calculating building structures (steel, cast iron, reinforced concrete, prefabricated monolithic reinforced concrete and others) to approximate the calculated models to the actual physical work of elements from various materials.

Monitoring provides for continuous monitoring in full-scale conditions for deformations and stresses in the load-bearing structures of the subway tunnels and verification of their compliance with design values ensuring accident-free operation of structures and includes:

– geodetic above-ground monitoring;
– geodetic underground monitoring;
– visual monitoring.
– instrumental monitoring of the state of structures;
– electronic remote monitoring;
– scientific support of monitoring activities.

Construction of the facility was carried out in 3 shifts without stopping traffic. Data transmission was carried out by all interested organizations on-line.

Scientific support included the following types of work:

– analysis of the results of geodetic observations (underground and above-ground monitoring) submitted by its organizations and recorded in a single database;

– provision of periodic reports containing monitoring results and their analysis, information on the state of the facility, possible deviations and forecast of changes in the state of engineering structures;

– control of geometric dimensions and position of the protective screen;

–conducting verification calculations and comparing the results with the spatial model, if necessary, correcting the model with the actual values obtained;

– clarification, taking into account the results of monitoring the types and amounts of further construction and installation work, developing recommendations in case of need for adjusting the design decisions, the timing of repair or restoration work, proposals for further monitoring.

Observations on the technical state of the structures of distillates tunnels during the construction work showed that the maximum vertical deformations were 11 mm, and the change in stresses in the cast-iron tubing of the lining reached 30 MPa (Figure 6).

Observation of the stressed-deformed state of the tunnel lining constructions allowed conducting construction and installation works around the clock.

At present, the tunnels of the underground are operated in a planned mode. Based on the results of inspection of defects that reduce bearing capacity, unacceptable rolls and other deformations of tunnel structures after the completion of construction have not been identified.

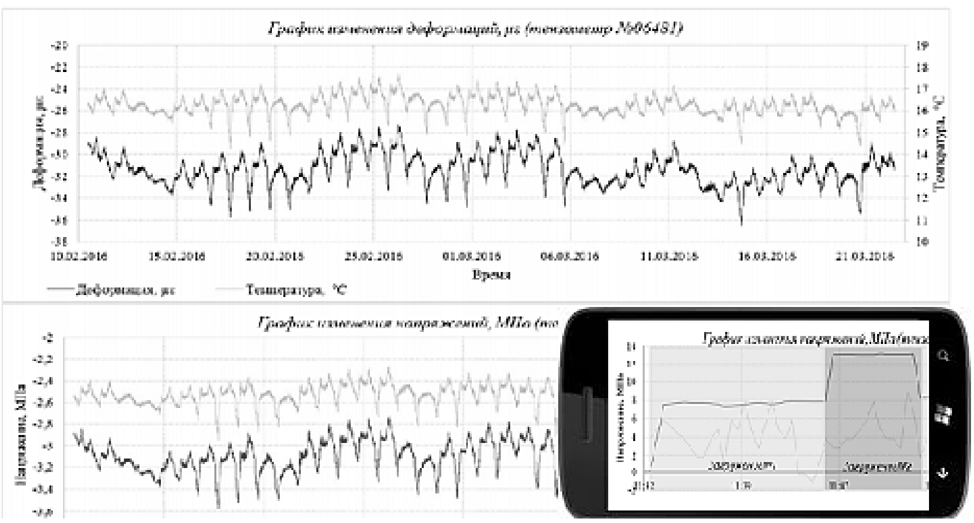

Figure 6 – Results of measurements and their display in specialized software

Conclusions

1. The Republican Unitary Enterprise «Belarusian Road Research Institute «BeldornNII» together with the Belarusian National Technical University prepared by the Ministry of Construction and Architecture of the Republic of Belarus from 01.01.2010 introduced technical codes of established practice (TKP EN) and national annexes to on the design of bridge structures, harmonized with the design standards of the European Union.

2. Harmonization of normative documents will contribute to improving the quality of construction, expanding the capacity of design and construction organizations to create bridge structures with a level of reliability that guarantees their safe operation during the project lifetime.

3. Experience in the operation of reinforced concrete structures of bridge structures shows that their reliability and durability depend on a large number of random factors that vary with time.

4. The design model of cross-sections of rod building structures is applicable for cross sections of arbitrary shape from any materials and is based on the use of transformed material deformation diagrams.

5. Refusal from the hypotheses of rock pressure and the transition to the theory of calculating underground structures on the basis of a deformation model using the deformation diagrams of materials of building structures and geomechanical models of the constituent soil massifs were introduced when monitoring the stress-strain state of structures.

6. The implementation of the adopted accounting regulations and the stress-strain state monitoring program allowed carrying out all construction and installation works on the operating tunnels in a short time.

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