To numerical approach for calculation of underground structures

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Abstract. The new approach for numerical calculating of stress and strain state of underground structures is presented in this issue. The advantage of this method is using in design scheme a real diagram of concrete and reinforcement materials. Also, these calculations are allowed to trace the process of deformation of reinforced concrete in each of the sections of the structure. In the technique, static calculations of reinforced structural elements when changing their initial conditions or stress state after strengthening are carried out taking into account new data. A three-dimensional finite element calculation is also carried out while taking into account regulatory loads. Assessment of levels of tangential and tensile stresses in walls makes it possible to target reinforcement and parameters of monolithic stiffness belts. Numerical results for discussion are presented in this paper.

1. Introduction

In Uzbekistan widespread subway practice is shallow bedding underground structures. Because the Central Asian region is a seismic prone area, domestic earthquake engineering meets specific problems. Especially it concerns subways structures. Therefore, the object of consideration here is underground structures from reinforced concrete.

In the practice of domestic metro construction when building underground metro stations by cut-and-cover techniques, the design of prefabricated reinforced concrete elements of 3-span frame systems is widely used. For conditions of Tashkent, where increased requirements are imposed on structures to ensure operation in the event of possible earthquakes, the seismicity of three-span stations built on the first line of the subway was ensured by four longitudinal monolithic reinforced concrete rigidity beams at the level of structure top formed by concreting reinforced ends from crossbars and floor slabs and heavy strongly reinforced chute. The goal of the issue is the presentation of the new numerical approach for strength’s calculation of subway structures by taking into account changing initial conditions at the calculation process. Existing building norms include simplified approaches. On the base of the finite element method, plastic deformations, crack propagation included in the presented method also.

In recent years, this design was improved due to an increase in the column pitch along the station axis (from 4.5 m to 6.0 m), which made it possible to slightly reduce the number of mounting units along the length of station platform section, but little changed the general architectural diversity of the station.
Tashkent subway is being constructed in complex engineering and geological conditions (water-saturated soils, etc.) using special methods (water drawdown, chemical soils solidification, etc.). With cut-and-cover techniques of tunnel construction, the surface is cut, tunnel structures are erected in the pit with pile timbering and slopes. Urban underground communications are shifted, ground traffic is set aside. The foundations and bases of buildings near the route are strengthened, if necessary.

Finished tunnel sections from reinforced concrete elements are installed using the cranes on a previously prepared base, after which the work is carried out to monolith the joints and waterproofing measures. In some stages (exit chambers, bells, joints of various types of lining), monolithic structures are used. At the end of tunnel main structures installation, the pit is backfilled with soil, sometimes service and technical facilities are built in the over-tunnel space.

In conditions of industrial production decline, a sharp rise in cost, and a decrease in new construction volume, the main reserve for saving material and labor resources is the extension of the service life of existing stations and tunnels. Their operating life is determined by a set of issues related to the quality of building materials, products and structures, design decisions, construction-installation works, and operating conditions of objects.

When using prefabricated structures in earthquake-prone areas, an essential condition is the arrangement of appropriate bracing between prefabricated elements, which allows achieving the lining reliability as a whole. First of all, the principle of strength balance of structures must be observed, i.e. the strength of nodes and joints of braced elements of the precast lining should ensure the transfer of longitudinal, compressive, and tensile forces and bending moments.
Tunneling experience shows that at the initial stages of object operation, some damage and defects are identified, the reasons for which are the violations of production methods of construction-installation works, the use of low-quality building materials, structures and products, deviation from the project during the production process and unsatisfactory operation of facilities.

For example, in existing column-type stations, cracks developed on the upper plates in the interface zone with internal reinforced concrete load-bearing walls. The width of these cracks can reach 5-10 mm, and they can be caused by neglecting the difference in a material strain of the load-bearing and enclosing walls.

To foresee the defects and damage means lead to the prevention of problems for construction. And as a consequence, strengthening and restoration of objects damaged during construction. Strengthening of reinforced concrete structures, as a rule, is associated with a change in their design scheme and stress state, with the combination of materials of different ages with different physic mechanical and geological properties in one structure, with the force redistribution in structure sections.

Existing methods of calculation do not allow considering with the required accuracy the actual stress-strain state of a structure during strengthening, the stages of its operation, its defects, and damage [1-6].

The most common strains are manifested in buildings and structures due to the nonuniform compressibility of the base soil (bedding and lenses of weak dusty-clay, loose sand peat and peat soils, and filled-in rock strata of different thickness). Great disadvantages are associated with the unaccounted for the cause of water traders and leaks from underground utilities, with mining operations near existing buildings [7,8]. A numerical approach with taking into account the hyperstatic reaction method of tunnel supports is realized in [9].

The practice of studying the technical condition of structures shows that damage is caused by the action of the following factors:
- operational wear - loss of bearing capacity from exposure to operational loads;
- changes in operating conditions, load increase due to changes in technological processes, the rebuilding of tunnel facilities or building superstructure;
- acquired structural defects resulting from improper operation of structures under dynamic and seismic effect;
- accidental damage, failure of individual structural elements during dismantling, transportation, and equipment installation processes.
Since the bearing capacity of structures can be changed to a greater or lesser extent (compared with the current one), these points should be taken into account when compiling a design diagram. Based on the analysis of technical documentation data (working drawings, acts on stripping works, etc.) and examination results, a design scheme is determined and engineering calculations of structure bearing capacity and the choice of the strengthening methods are performed.

Static calculations of reinforced structural elements when changing their initial static position or stress state after the strengthening should be carried out considering the new static circuit or the stress state of the element.

So approaches like a model of box-shaped structure and calculation on its basis [10-13] too much complicated and not reliable. Using the bimoments in this approach can be used for ground structures and not for underground ones. In calculation vital to take into account structure-soil-structure interaction and so approaches exist now [14]. Seismic response of interaction systems like underlying tunnels, soils, and frame structures wide investigated [15,16] too. However, the proposed approach with three-dimensional finite element calculation more comprehensive.

The forces acting in the elements of static indefinable reinforced concrete structures are recommended to be calculated (taking into account plastic deformations) and limited to up to 30%.

The scheme and reinforcing method of beams during bending are selected depending on the ratio between the relative heights of the compressed zone of concrete. It is determined from the corresponding equilibrium conditions, depending on the boundary value of the relative height of the compressed zone of concrete and the presence of defects in concrete in the compressed zone, the state of reinforcement in the stretched zone of the beam. To ensure reliable and high-quality restoration of reinforced concrete structures, as well as their quick commissioning, repair materials should, first of all, meet the following requirements:

- to possess high adhesive and cohesive capacity, exceeding the same indices for concrete;
- to have a quick strength gain;
- to have low creep and shrinkage;
- be resistant, if necessary, to the effect of chemicals, water, and atmospheric element.

The above concrete and mortar are used to eliminate the following damage that occurs in underground and above-ground reinforced concrete structures:

- Cracks in concrete;
- Concrete chips with or without reinforcement exposure;
- Sections of weak concrete;
- Exposed reinforcement;
- Leaching of concrete with caverns and voids damage formation in it on the block surface with or without reinforcement exposure.

Usually, the situation is aggravated by an incorrect choice of calculation models and methods for calculating the basic load-bearing elements of buildings (an incorrect assessment of real rigidity of building structures and their interfaces, an insufficient account of physical and geometric eccentricities of load application, neglect in load stages). A complex stress state arises in prefabricated-monolithic
structures when connected to escalator structures outside the outer walls of separately standing reinforced concrete racks accepting asymmetric loads. Due to the difference in strains, the cracks usually occur in the wall structures resting on the racks.

Recently, the technology of computer research of monolithic and multi-story stone houses, shells and other structures has been developed, which allows calculating complex statically indefinable building systems as a whole, more correctly accounting the joint manifestation of the basic loads and temperature effect, and obtaining all components of the stress state of materials at any point, clear patterns of structure strain, the required reinforcement of building elements. If necessary, a deeper analysis of the effect of plastic strains and cracks is carried out.

The indicated direction of research coincides with world trends in the field of building design. It is known that the calculation procedure according to existing standards is focused on manual calculation methods, on separate accounting of a series of loads and influences; it allows conditional "dismemberment" of structures into simple elements. With this simplification, the strength calculation is carried out by neglecting internal efforts but considering conditionally accumulated loads without their redistribution, temperature effect, and other components. A high level of computer technology eliminates these shortcomings.

One of the most important advantages of computer research technology, available in computational mechanics, is the ability to perform complex calculations of the structure as a whole while taking into account combinations of loads, natural and industrial impacts, or the ability to analyze the impact of individual effects. The use of modern technologies in the calculations allows us to identify the zones of greatest tensile stresses in structures, to predict the places of possible cracking in the walls and to determine the required strengthening in such zones.

The presence of all stress components makes it possible to more correctly assign the strength parameters of materials in compressed elements and transfer zones of great concentrated loads. So, in the actual biaxial or triaxial stress state, the calculation is made for uniaxial compression only. Here, an incorrect determination of the strained (and, accordingly, stressed) state of variously loaded conjugate walls is allowed.

An account for the forces redistribution between vertical load-bearing elements in calculations allows more reasonably distribute the loads to the chutes, to prevent their overstress in the slabs due to the load redistribution between individual walls.

Much higher accuracy is provided by two-dimensional and three-dimensional finite element calculations with simultaneous allowance for basic loads. Evaluation of the levels of tangential and tensile stresses in the walls allows the targeted assignment of reinforcement and parameters of monolithic stiffness belts.

2. Methods

Well known that two-dimensional or three-dimensional consideration of structures in the numerical calculation is much precise then one-dimensional ones. Here evaluation of levels of tangential and tensile stresses in the walls allows targeted assignment of reinforcement and parameters of monolithic stiffness belts.

Moreover an account for forces redistribution between vertical load-bearing elements allows more reasonably distribute the loads to the chutes, to prevent their overstress in the slabs due to the load redistribution between individual walls.

The whole-section lining is a three-dimensional closed reinforced concrete frame (Fig. 4). The inner dimensions of the whole-section lining are taken as height - 4610 mm, width - 4150 mm; the thickness of the lining elements at a filling height above the tunnel from 1 to 7 m and the water-table level 1 m below the ground surface is: for a crossbar - 250 mm, for a chute -220 mm, for the walls - 190 mm. For the lining of standard size, the design class of concrete is taken: for compressive strength - B25, $R_c = 14.8 \, MPa$, for tensile strength - $R_{tc} = 1.07 \, MPa$, elastic modulus - $E_b = 30000 \, MPa$. The lining is reinforced with welded nets and frames made of classes A-I, A-II and A-III.
reinforcement. The thickness of the protective layer for the principal reinforcement is 15 mm, the pitch of the principal reinforcement is 0.10-0.15 m.

According to [2], the calculation of the whole-section lining is performed for one of the main combinations of loads. It provides for symmetrical loading from the transport on the lining surface located above the tunnel [17]. The lining is subject to standard fixed vertical and horizontal loads from the weight of the road paving, the backfill soil above the tunnel, the hydrostatic pressure of groundwater above the tunnel at the level of the chute axis, the dead weight of the lining, the horizontal soil pressure at the level of the crossbar and the chute axes (Figure 5).
The intensity of the basic loads from the automobile transport on the road surface is taken depending on which of them will give the greatest value at the level of the crossbar lining axis [18]. Some authors used a box-shaped structures model for underground objects too [19-21]. This approach took into account interaction forces and moments in the contact zones of beam and plate elements. However, this method is not applicable in our case.

So, the loads and impacts on the whole-section lining following the normative requirements and other standards were calculated by the “TashMetroProekt” Institute for the following data:

loamy soil, standard volume weight \( \gamma = 0.018 \text{MPa} / \text{m} \);
the standard angle of internal friction of soil \( \varphi = 24^\circ \);
the maximum groundwater level located 1 m below the surface;
 modulus of soil elasticity \( E = 50 \text{MPa} \);
soil bearing reaction \( R \), with a coefficient of soil reaction \( k = 5 \text{MPa} / \text{m} \);
the tunnel depth relative to the surface \( H = 4 \text{m} \);
road paving thickness \(-2 \text{m}\).

The total vertical standard and calculated constant loads for the first group of limit states to calculate the loads 1 are:

- the load acting on the lining at the crossbar level (pressure from the road paving, backfill weight above and below groundwater level, additional vertical pressure due to the presence of groundwater, the dead weight of the crossbar, temporary load according to the NK-80 scheme (it turned out to be higher than AK-11)

\[
q_{p,\text{norm.}} = 0.09351 \text{MPa} \quad q_{p,\text{calc.}} = 0.10719 \text{MPa} / \text{m}
\]

horizontal pressure acting on the lining at the level of crossbar and chute axles

\[
P_{ah1,\text{norm.}} = 0.0112 \text{MPa} \quad P_{ah1,\text{calc.}} = 0.02215 \text{MPa} \quad P_{ah2,\text{norm.}} = 0.0448 \text{MPa} \quad P_{ah2,\text{calc.}} = 0.05277 \text{MPa}
\]

the intensity of additional horizontal pressure due to the presence of groundwater at the level of crossbar and chute axles

\[
P_{hw1,\text{norm.}} = 0.01858 \text{MPa} \quad P_{hw1,\text{calc.}} = 0.01974 \text{MPa} \quad P_{hw2,\text{norm.}} = 0.04762 \text{MPa} \quad P_{hw2,\text{calc.}} = 0.05058 \text{MPa}
\]

Calculation of tunnel lining was carried out using two design schemes:
1. An existing scheme used in Uzbekistan (Figure 6)
2. A scheme of the technique developed by the authors (Figure 7)
The model uses a linear scheme for determining internal forces. The height of the compressed zone is determined (Figure 6) after calculating the internal forces according to [1]:

\[
x = \frac{R_A A_A - R_A^C A_A^C}{R_b b}
\]

Here \( R_b \) is the calculated resistance of concrete to compressive strength, \( R_A^C \) is the calculated reinforcement resistance to compression, \( R_A \) is the calculated tensile strength of the reinforcement, \( A_A \), \( A_A^C \) are the cross-sectional areas of the reinforcement in tensile and compressed zones. Here, the
conditions $\xi \leq \xi_R$, $\xi = x / h_o$, $\xi_R = \frac{\omega}{1 + \sigma_{SR} (1 - \frac{\omega}{1.1})}$, should be satisfied; $\omega$ - is the characteristic of the compressed zone of concrete, determined by the formula $\omega = 0.85 - 0.008 R_b$, here $\sigma_{SR} = R_s$, $a$, $a'$, are the distances from the resultant forces in the reinforcement to the nearest edge of the section. The cross-section strength is ensured if the calculated moment from the external load does not exceed the calculated moment of internal forces relative to the center of gravity of the cross-section of the tensile reinforcement or relative to the center of gravity of the compressed zone of concrete (Figure 8)

$$M \leq R_b b x (h_0 - 0.5 x) + R_{SC} A'_S (h_0 - a')$$

Table 1 shows the data calculated by the above formulas, for checking the strength of the normal section for the crossbar, wall, and chute. To check the strength of the cross-section at the maximum moment, calculated by the Central Scientific Research Institute of transport engineering model, we can write:

| №   | crossbar | wall | chute |
|-----|----------|------|-------|
| $h$, m | 0.25 | 0.22 | 0.19 |
| $b$, m | 1 | 1 | 1 |
| $a$, m | 0.025 | 0.025 | 0.025 |
| $a'$, m | 0.025 | 0.025 | 0.025 |
| $h_0$, m | 0.225 | 0.195 | 0.165 |
| $R_b$, MPa | 14.8 | 14.8 | 14.8 |
| $\omega$ | 0.7316 | 0.7316 | 0.7316 |
| $\xi_R$ | 0.560353 | 0.560353 | 0.560353 |
| $R_s$, MPa | 365 | 365 | 365 |
| $R_{sc}$, MPa | 365 | 365 | 365 |
| $A_s, m^2$ | 0.002512 | 0.00266 | 0.004832 |
| $A'_s, m^2$ | 0.001206 | 0.002512 | 0.00201 |
| $x$ | 0.032215 | 0.00364 | 0.069618 |
| $\xi$ | 0.43176 | 0.018665 | 0.421926 |
| $M$, MPa · m³ | 0.187616 | 0.166276 | 0.236832 |
For the crossbar $0.134\, MPa \cdot m^3 < 0.187616\, MPa \cdot m^3$
For the wall $0.089\, MPa \cdot m^3 < 0.166276\, MPa \cdot m^3$
For the chute $0.213\, MPa \cdot m^3 < 0.236832\, MPa \cdot m^3$
Figure 11. Calculation Results.

Figure 12. Isochromes of principal stresses $\sigma_1$ in the structure.
Next, calculate the lining, the design scheme of which is shown in Figure 9, considering the nonlinear strain of its material (here the values of all limit tensile strengths are given above are taken into account).

3. Results and discussion

Figure 10 shows the structure strain under the symmetrical load, and Figure 8 shows the points where tensile stresses in concrete exceed their limit values (obtained from calculations).

In a reinforced concrete structure, high compressive stresses occur, mainly, at the joints of various lining elements with each other (floor-wall, wall-chute). The maximum value of compressive stress was 10.889 MPa, which did not reach the limit compression value of concrete equal to 14.8 MPa. This is due to the presence of longitudinal reinforcement in the compressed zone. The tensile stresses in the reinforcement of the destroyed parts of concrete were maximal and their values did not exceed 16.43 MPa. Figures 9 and 10 show the averaged values of the principal stresses $\sigma_1$ and $\sigma_2$ obtained in calculations. From these figures, we can see the points of stress concentration. On the whole, the data obtained confirm the results of the TsNIIS model. But it should be noted that the values of bending
moments calculated by the author in an inelastic statement (design) turned out to be 20-25% less than the ones shown in Figure 7.

Experiments shows [19-21] that the calculation methods used in practice do not sufficiently take into account the complexity of loading the structural elements and, in particular, after the formation of crack. It leads to the need for monitoring the state of the structure during its operation up to destruction.

Studies have also shown that in building structures when systems move from static indeterminacy to static definability, a redistribution of internal forces occurs. It leads to the necessity of stress and strain state estimation of reinforced concrete structures. The calculation method, that is as close as possible to the actual work of the reinforced concrete structure is created and applied here.

4. Conclusions
1. Numerical results obtained by the TsNIIS model give overestimated values for bending moments up to 20-25% compare by the proposed approach.
2. The tensile stresses in the reinforcement damaged parts (crack zones) of concrete are the highest. The main drawback and vulnerability of the TsNIIS model are using internal forces calculated from the elastic case. It leads to high values for strains and as a consequence for the wrong estimation of bearing capability for the whole structure.

And the most important advantage of the proposed method is using the calculation of real diagrams for concrete and reinforcement deformation. Moreover you can visual viewing and tracing the pattern of the strain of the reinforced concrete structure in each of its sections. The proposed approach is much comprehensive than the previous one and can take into account plasticity. It is so vital in seismic zones and at soil-structure interaction problems.

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