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Forecast of the stress-strain state of the prefabricated lining of underground tunnels of curvilinear cross-section

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A well-developed transportation system ensures economic growth in most countries. Improving its quality through the construction of tunnels is one of the most common practices in many countries of the world. The length of tunnels increases significantly, they are combined into a developed network, so there is a need to increase traffic capacity. To meet the growing demand for transportation, tunnels occupy an increasingly large area and the number of lines is growing. Usually, the circular shape of the tunnel section is used in the construction of deep-level tunnels. Currently, it is the most common in the world due to the development of shield tunneling and significant supporting strength of the tunnel lining in comparison with other cross-sectional shapes. However, the efficiency ratio of the section remains small; the rectangular shape of the section shows to good advantage by this indicator. The authors of this work have combined the advantages of circular and rectangular shapes of the tunnel section into a new form - quasi-rectangular.
The aim of the paper is to study the operation of the lining of a quasi-rectangular tunnel. The study of the stress state of the lining was performed on the basis of numerical simulation using the Plaxis 2D software package.
Results show that the flexure moment and normal forces in the lining of the quasi-rectangular tunnel are respectively 6.5 and 1.023 times higher than when using the circular cross-sectional shape, however, taking into account the traditionally used thicknesses of the lining, the quasi-rectangular tunnel lining remains stable. With the same safety margin of structures, the area of a circular tunnel should be 1.25 times larger compared to a quasi-rectangular tunnel.

Keywords: tunnel; curvilinear cross section, optimization, lining, stress state, pattern of interaction.

Introduction

Nowadays, the most common form of cross-section of urban transport tunnels is circular. Due to the circular shape of the tunnel, its lining has the greatest supporting strength. The construction of such tunnels is carried out using tunnel boring machines by the earth pressure balanced tunneling method or without it. The circular cross-section shape of the tunnel is also used for double-track tunnels, the diameter of which is significant and usually exceeds 10 m. At the same time, the construction cost of a double-track tunnel is less than the construction of two single-track tunnels. In addition, the cost of a double-track tunnel can be further reduced in comparison with two single-track tunnels by changing its shape from circular to elliptical, horseshoe-shaped or rectangular (Fig. 1) [1]. The disadvantage of the circular shape of tunnels is the low efficiency ratio of the cross-sectional area. Thus, the tunnel has a large cross-sectional area, which ultimately increases the cost of construction. Meanwhile, although the approximation of the cross-sectional shape to a rectangular one allows more efficient use of its area, the drawback of this approach is the increase in stress concentration in the corner zones of the tunnel lining. Therefore, the intermediate shape between the circle and the rectangle will allow both to increase the efficiency ratio of the cross section in comparison with the tunnel of circular shape, and to reduce stress concentration in the corner sections of the lining, which ultimately will reduce the cost of construction.

Currently, the existing tunneling equipment and the adopted construction technology make it possible to efficiently build tunnels not only of circular shape, but also of a more complex one, to design various cross-sectional shapes of the tunnels. Thus, the search for the optimal shape of the cross section of the tunnel, on the one hand, is not limited by the technological capabilities of construction using tunneling machines, and on the other hand, it is promising from the point of view of reducing the cost of tunnels construction. The works [3, 4] present the experience of construction of tunnels of curvilinear shape.

1. Methods and methodology of work

1.1. Technology of construction with the help of the tunnel boring machine

The tunnel boring machines allowing construction of tunnels, the cross-section shape of which differs from the circular shape, have been tested to a sufficient degree at underground construction facilities in Japan and China (Fig. 2) [5, 6]. For example, the tunnel boring machine was used for the Fukutoshin underground line in Tokyo enabling to form an oval-shaped cross section of the tunnel. The length of the Baicheng underground line in China is 3.345 km. It was built using the tunnel boring machine, which allows you to construct domed shaped and horseshoe-shaped tunnels.

The curvilinear cross-section shape of the tunnels (Fig. 3, b) is often used for double-track tunnels due to the following advantages: it allows you to reduce the width and height of the section; the efficiency ratio of the cross-sectional area increases.

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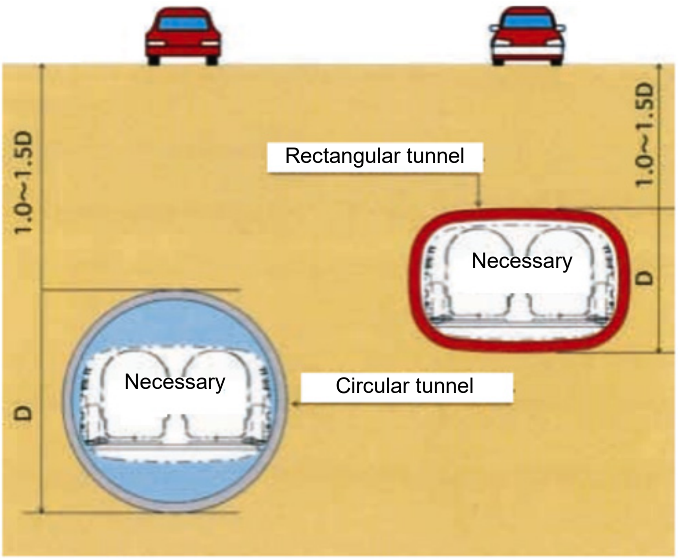

Figure 1. Comparison between circular and rectangular shapes [2].
Рисунок 1. Сравнение между круговой и прямоугольной формами [2].

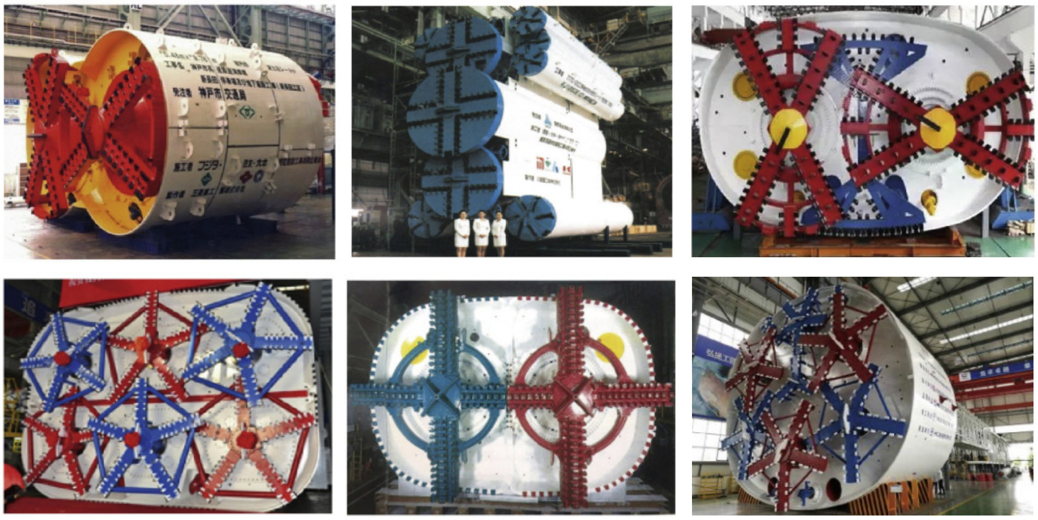

Figure 2. Designs of tunnel boring machines for tunnels of curvilinear shape [7].
Рисунок 2. Конструкции щитовых комплексов для тоннелей криволинейного очертания [7].

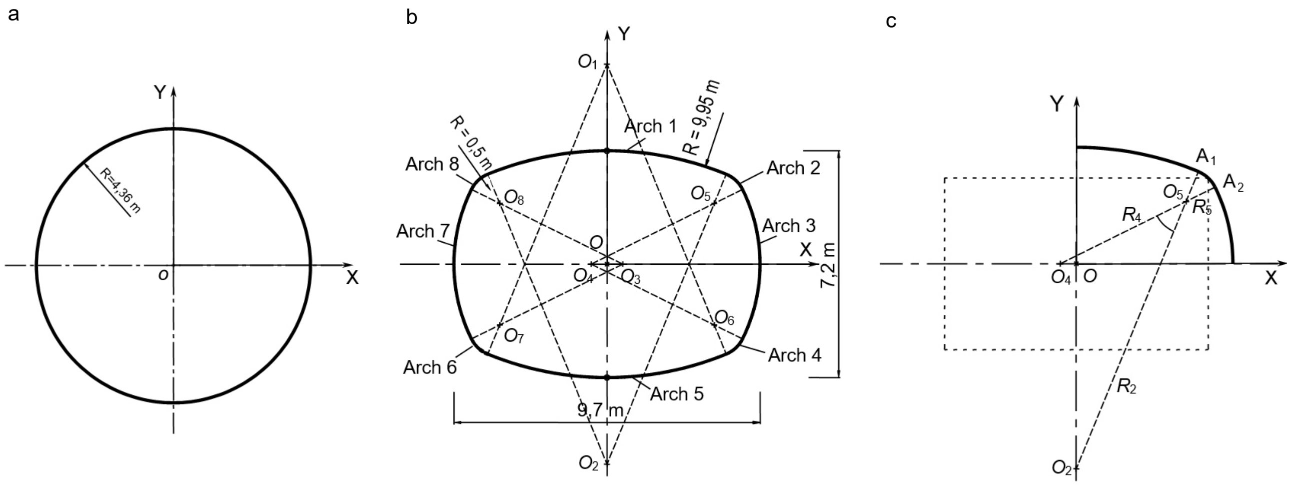

Figure 3. The tunnel of circular cross section (a), curvilinear cross section (b) and the diagram for determining the shape and size of the curvilinear section of the tunnel (c).
Рисунок 3. Тоннель кругового поперечного сечения (а), криволинейного поперечного сечения (б) и диаграмма определения формы и размеров криволинейного сечения тоннеля (в).

Tunnels with a complex cross-sectional shape have a significant drawback, the supporting strength of the lining of such tunnels, ceteris paribus, is lower than in tunnels of circular shape (Fig. 3, a). However, this disadvantage can be overcome through the development of more advanced building materials, including fiber reinforced shotcrete, and due to the rational choice of the curvilinear outline of the lining as well [8–10].

The work considers a tunnel of curvilinear cross-section, the construction of which is conducted from 8 centers – from O_1 to O_8. Internal dimensions are determined by the shape of the rectangular construction clearance, which is set based on the requirements of regulatory documents. The construction is done as follows. The first step is to select the location of the O_5 center. Then a circle with radius $R_5 = O_5A$ is drawn. O_5A_1 and O_5A_2 are drawn through points A_1 and A_2;O_2 and O_4 are marked at the intersection with OX and OY axes. Finally, circles with radius $R_2 = O_2A_1$ and $R_4 = O_4A_2$ are constructed (Fig. 3, c). The resulting construction must be mirrored to the remaining three quarters. Fixed values of geometric parameters of the tunnel are accepted in the work but an algorithm is being developed to optimize the geometric parameters of the adopted shape of the cross section of the tunnel, which will determine their most rational parameters based on the stress factor of the tunnel lining, taking into account the specified efficiency ratio of the tunnel section. The optimization algorithm will be based on the solution of the problem by the HRM method [11]. Testing of the stress condition of the tunnel lining will be carried out on the basis of solving the problem of mechanics of underground structures based on the scheme of joint interaction "lining-soil mass". The statement of the problem of determining the stress state of the lining according to the joint interaction scheme is presented in the next section.

1.2. Building a numerical model for forecasting the development of lining strain-stress state during the construction of a tunnel of curvilinear shape

The work considers the forecast of the development of the stress-strain state of the tunnel lining of curvilinear cross-section and compares it with the stress state of the lining of a circular shape. The depth of the tunnel is assumed to be 10 m, the groundwater level is 0.5 from the surface of the earth. The construction of the tunnel is carried out by the tunnel boring machine with the construction of a prefabricated lining in the tail section, under the protection of the shield shell. The parameters of the cross section of the tunnel of curvilinear cross section and the main parameters of the lining are given below.

Calculation of the stress state of the lining according to the interaction scheme enables to present the nature of transmission of loads from the rock mass to the lining of the tunnel as a result of their joint interaction. When considering a tunnel with curvilinear cross-section, both quasi-analytical methods (N. N. Fotieva) and numerical methods of analysis can be used for calculation using the joint interaction scheme [12]. The latter have advantages due to the possibility of specifying undirected boundary conditions, as well as taking into account nonlinear deformation of the soil mass in explicit form by defining an elastic-plastic model of the environment [13] or models based on the theory of the modified theory of deformation plasticity (Hypoplasticity) [14]. The hardening soil model is adopted as a model of deformation of the soil mass, which was widely used in solving the problems of forecasting the load on the lining of underground structures[15], as well as the prediction of subsidence of the earth's surface

Parameters of the finite element scheme.
Параметры конечно-элементной модели.

Width *B*, m	9.70
Tunnel height *H*, m	7.20
External radii, m	
R_1	9.95
R_2	9.95
R_3	5.35
R_4	5.35
R_5	1.00
R_6	1.00
R_7	1.00
R_8	1.00
Thickness of the lining *m*, m	0.50
The cross-sectional area of the tunnel *S*, m²	59.70

Physico-mechanical characteristics of the soil and lining material.
Физико-механические характеристики грунта и материала обделки.

Parameter	Concrete	Soil
Specific weight γ, kN/m³	24	19.5
Effective cohesion *s*, kN/m²	–	7
Effective angle of internal friction φ, deg	–	20.5
Angle of dilatancy ψ, deg	–	4.81
Poisson's ratio ν	0.15	0.35
Modulus of deformation *E*, MPa	35 000	–
Modulus of deformation E_{50}^{ref}, MPa	–	32.5
Modulus of deformation E_{oed}^{ref}, MPa	–	32.5
Modulus of volume elasticity E_{ur}^{ref}, MPa	–	97.5
Indicator *m*	–	0.5

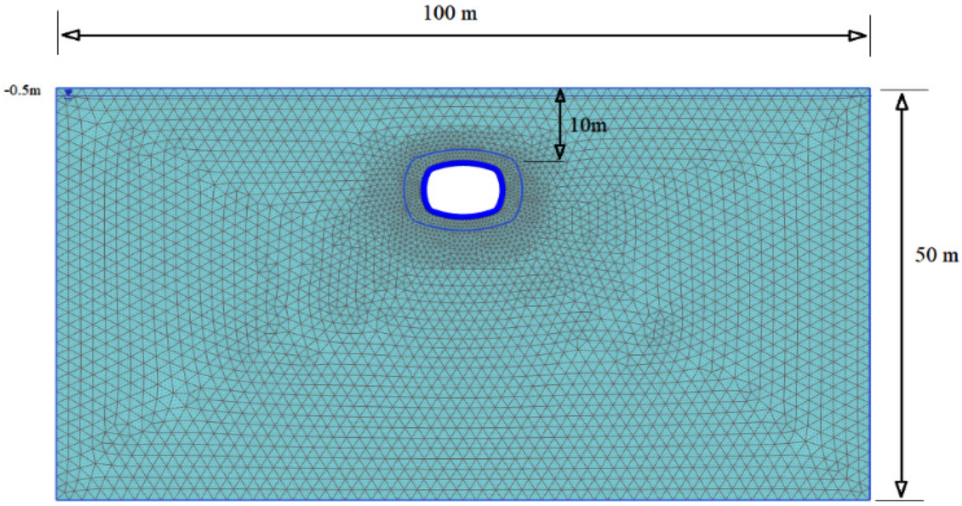

Figure 4. The finite element scheme for predicting the development of a stress-strain state in a tunnel lining.
Рисунок 4. Конечно-элементная модель прогноза развития НДС в обделке тоннеля.

[16, 17]. The model is a class of models with double hardening, where the shearing plastic deformations and volumetric plastic deformations meet the corresponding surface of plastic currents and plastic potential.

The surfaces of the plastic flow are not fixed in the space of main stress but can expand isotopically, which allows modeling both mobilization of soil strength and plastic volumetric contraction. This generally allows the model to be applied in a wide range of changes in the mechanical behavior of sandy and clay soils.

When performing numerical simulation, the computational space was divided into triangular 15-node elements (Fig. 4). Rod elements are used for modeling the tunnel. Numerical model size: width is 100 m, height is 50 m; model consists of approximately 6680 elements. Displacements along the bottom boundary of the model are not allowed in both directions; displacements in the horizontal direction are not allowed along lateral boundaries of the model. The problem was solved in gravitational setting.

Physico-mechanical characteristics of soils and lining of the tunnel are given in table below.

In order to compare the distribution of internal forces in the lining of the tunnel with curvilinear cross-section and the lining of a circular tunnel, two numerical models were constructed where the lining of the tunnel is located under similar conditions, the cross-sectional area of which is equal to each other $S_C = 59.7$ m^2, while the equivalent diameter of the circular shape tunnel R was 4.36 m.

2. Analysis of the development of the stress-strain state of the prefabricated lining of the curvilinear tunnel

The results obtained on the basis of numerical calculations performed on the Plaxis software package show (Fig. 5) that the largest moment in the lining of a tunnel of a quasi-rectangular shape is 0.4916 (MN × m)/m compared to 0.0755 (MN × m)/m in the lining of the tunnel of a circular cross section. The maximum longitudinal force is 1.139 MN/m and 1.113 MN/m, respectively. The results show that the internal force in the lining of the tunnel with a curvilinear cross-section shape is greater than in the lining of the tunnel with a circular cross-section by about 1.023 times, the bending moment is 6.5 times. The performed assessment of the lining strength allows us to say that the supporting strength of the lining of the tunnel of curvilinear cross-section is still provided, however, it is necessary to increase the percentage of reinforcement of its section. The useful cross-sectional area of the curvilinear tunnel is 1.25 times larger than the circular shape tunnel.

To estimate the influence of the lateral pressure coefficient on the strain-stress state of the lining of the tunnel of curvilinear cross-section, a number of calculations were performed where the parameter K (coefficient of passive earth pressure) varied from 0.25 to 1.0. The calculation results are presented in the form of diagrams of flexures moments and normal forces (Fig. 6).

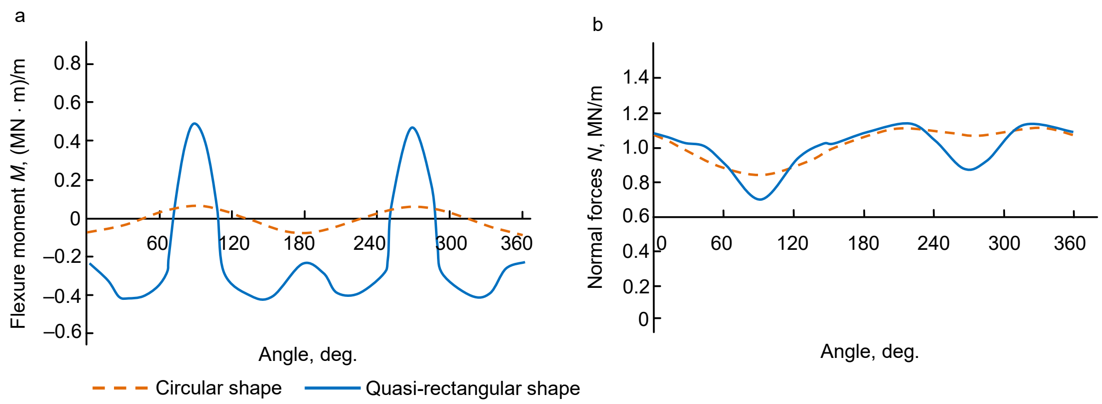

Figure 5. Bending-moment diagram (a) and normal force diagram (b) in a prefabricated tunnel lining for quasi-rectangular and circular shapes (the angle is measured counterclockwise on the right axis).
Рисунок 5. Эпюры изгибающего момента (а) и продольной силы (б) в сборной обделке тоннелей для квазипрямоугольной и круглой форм (угол измеряется против часовой стрелки по оси справа).

The results showed that when changing the coefficient of passive earth pressure *K* from 0.25 to 1.0, the normal force in the sides of the prefabricated lining of tunnels of various shapes did not change significantly, but the normal force in the section from the sides to the arch of the prefabricated lining tunnels increase with increasing coefficient of passive earth pressure. The magnitude of the flexure moment (in absolute value) in the prefabricated tunnel lining decreases with increasing coefficient of passive earth pressure. The results show that the maximum flexure moments between the circular and curvilinear cross section of the tunnel have a large difference, while the gap between normal forces is insignificant.

To estimate the influence of the deformation characteristics of the soil mass on the strain-stress state lining of the tunnel of curvilinear cross section, a number of calculations were performed, where the parameter E_{50}^{ref}, varied from 5 MPa to 75 MPa. The results show that the flexure moment in the lining of the tunnel decreases with increasing deformation modulus *E*. In this case, the maximum normal force decreases slightly. The maximum flexure moment is 0.781 (MN × m)/m and 0.376 (MN × m)/m, the maximum normal forces are 1.199 MN/m and 1.120 MN/m, the corresponding deformation modulus *E* is 5 MPa and 75 MPa. For both circular and quasi-rectangular tunnel shapes, it can be noted that as the deformation module increases, bending moments and normal forces decrease.

In order to estimate the influence of soil mass cohesion on the strain-stress state lining of the tunnel of curvilinear cross section, a number of calculations were performed, where the parameter *C* varied from 0 kPa to 300 kPa. The results show that the amount of soil mass cohesion does not significantly affect the maximum bending moment and maximum normal force. These results also correspond to the results of M. Palassi [15], who studied the formation of a stress state in the lining of a circular-shaped tunnel.

4. Conclusions

The performed studies allow us to draw the following conclusions:

– during the construction of tunnels under similar conditions, the internal forces induced in lining a tunnel with a circular cross section is lower than in a tunnel with a curvilinear cross section; while the normal forces differ slightly, and bending moments differ by more than 6 times, the tunnel shape has a greater influence on the bending moments than on the normal forces;

– the tunnel with curvilinear cross-section shape has a higher cross-sectional efficiency ratio compared to a circular shape tunnel, which can reduce the cost for construction of a tunnel with a significant length;

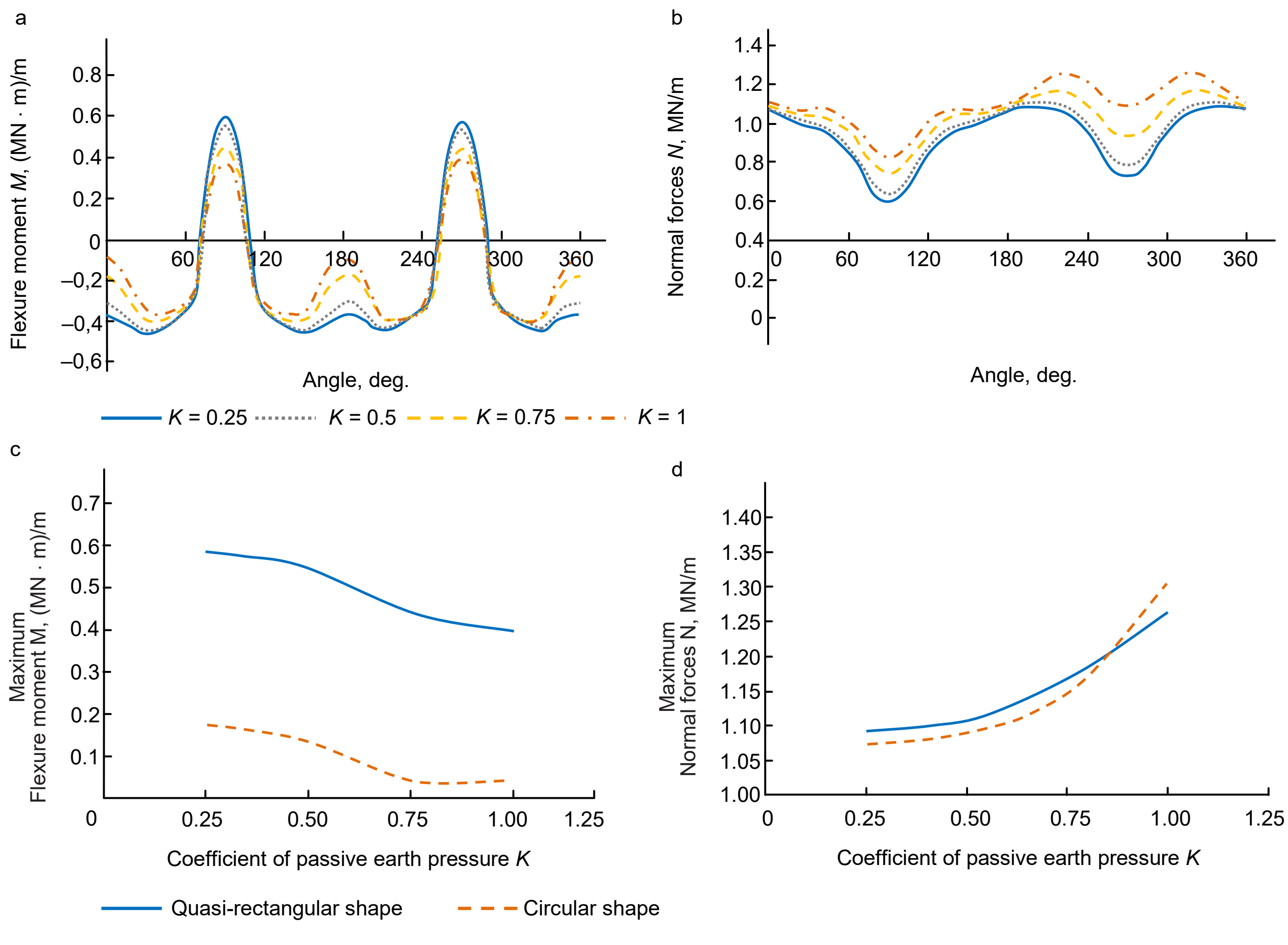

Figure 6. Bending-moment diagram (a) and normal force diagram (b) in the prefabricated tunnel lining for different values of the coefficient of passive earth pressure *K* and the maximum bending-moment diagram (c) (M_{max} = | M_+, M_- |) and maximum normal force (g) in the prefabricated tunnel lining for curvilinear and circular cross-sectional shape depending on the coefficient of passive earth pressure *K*.

Рисунок 6. Эпюры изгибающего момента (а) и продольной силы (б) в сборной обделке тоннелей для различных значений коэффициента бокового давления *K* и эпюры максимального изгибающего момента (в) (M_{max} = |M_+, M_-|) и максимальной продольной силы (г) в сборной обделке тоннелей для криволинейной и круговой формы поперечного сечения в зависимости от коэффициента бокового давления *K*.

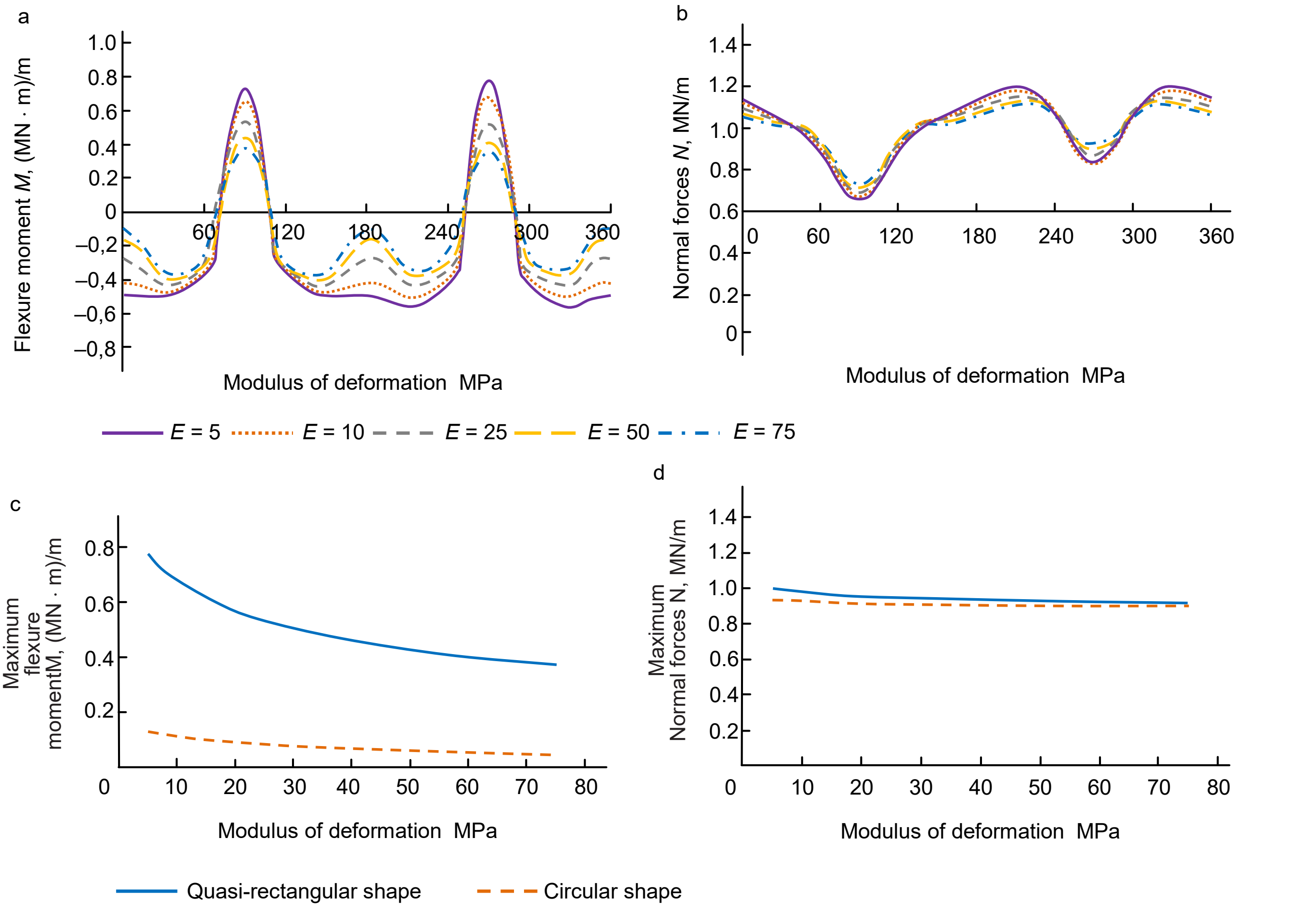

Figure 7. Bending-moment diagram (a) and normal force diagram (b) in the prefabricated tunnel lining for various values of the deformation modulus *E* and diagrams of the maximum bending moment (c) and maximum normal force (d) in the prefabricated tunnel lining for curvilinear and circular shapes depending on the deformation module *E*.

Рисунок 7. Эпюры изгибающего момента (а) и продольной силы (б) в сборной обделке тоннелей для различных значений модуля деформации *E* и эпюры максимального изгибающего момента (в) и максимальной продольной силы (г) в сборной обделке тоннелей для криволинейной и круглой форм в зависимости от модуля деформации *E*.

– the advanced tunnel boring machine can be designed for various cross-sectional shapes and for curvilinear cross-section as well, so the equipment for the construction of such tunnels is not a limiting factor;

–the search for a more optimal shape of tunnels of curvilinear shape for specific engineering and geological conditions will reduce stress in the lining.

Further research will be aimed at developing an algorithm for optimizing the parameters of a quasi-rectangular cross-section, providing optimal tunnel curvature parameters from the point of view of the development of the strain-stress state in the lining.

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Прогноз напряженно-деформированного состояния сборной обделки тоннелей метрополитена криволинейного поперечного сечения

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Для экономического роста большинства стран требуется хорошо развитая транспортная система. Повышение ее качества за счет строительства тоннелей является одной из наиболее распространенных практик во многих странах мира. Длина тоннелей значительно увеличивается, они объединяются в развитую сеть, появляется необходимость увеличения пропускной способности. Чтобы удовлетворить растущий спрос на перевозки, тоннели занимают все большую площадь и количество линий растет. Традиционно при строительстве тоннелей глубокого заложения применяется круговая форма сечения тоннеля, в настоящее время она является наиболее распространенной в мире из-за развития щитовой проходки тоннелей и значительной несущей способности обделки тоннелей по сравнению с другими формами поперечного сечения. Однако коэффициент использования сечения остается небольшим, по этому показателю выигрывает прямоугольная форма сечения. Авторы работы объединили преимущества круговой и прямоугольной форм сечения тоннеля в новую форму – квазипрямоугольную. Целью статьи является изучение работы обделки тоннеля квазипрямоугольной формы. Изучение напряженного состояния обделки выполнено на основании численного моделирования с использованием программного комплекса Plaxis 2D. Результаты моделирования показывают, что изгибающий момент и нормальные силы в обделке тоннеля квазипрямоугольной формы оказываются соответственно в 6,5 и 1,023 раза выше, чем при использовании круговой формы сечения, однако с учетом традиционно применяемых толщин обделок обделка тоннеля квазипрямоугольной формы сохраняет устойчивость. При том же габарите приближения строений площадь круглого тоннеля должна быть в 1,25 раза больше по сравнению с квазипрямоугольным тоннелем.

Ключевые слова: тоннель; криволинейное поперечное сечение; оптимизация; обделка; напряженное состояние; схема взаимодействия.

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