TRANSPORT IMMERSED TUBE TUNNELS

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ABSTRACT

The article shows advantages and disadvantages of immersed tube tunnels used in the transport passage across extensive water obstacles (straits, lakes, wide rivers). An immersed tunnel project for the passage at the intersection of a strait, which may be the most cost-effective, reliable and affordable in terms of costs, time of construction and choice of technologies, is evaluated. The authors propose a method for calculating the tunnels with account for seismic impact.

ENGLISH SUMMARY

Background. *Traditionally, extensive transport passages across straits and wide rivers were constructed using bridges. In some cases, for the passage of high-tonnage vessels superstructures have to be located on high bearings. This complicates the entire structure and makes it necessary to lengthen approaches to bridges.*

One of the possible solutions of the problem is the construction of shield tunnels. However, in this case, there is a requirement, which causes lengthening of the passage: the tunnel should be located 25–30 meters or more below the bottom of the water basin.

Immersed tube tunnels have a relatively smaller extension, they are located at the bottom of water basins with a small deepening, and therefore approaches to them may be relatively short. The length of a bridge passage at the crossing of a water obstacle on a flat ground increases significantly (Pic. 1 [1]).

Immersed tube tunnel consists of large built-up concrete or steel-concrete sections. Sections of tunnels are produced on the shipbuilding ways of shipyards, dry docks or in temporary pits (Pic. 2 [2]).

The butt ends of the sections are sealed with temporary partitions, then pits or dry docks are filled with water, the sections float and they are hauled to the installation site. Then they are immersed in a prearranged trench at the bottom of the water basin and connected to the previously installed sections (Pic. 3 [1]).

After installing sections of the tunnel at the bottom, the trench around it is filled, and the bottom surface of the water basin is restored, the tunnel should have a protective layer of ground of at least 1,5 m for protection from sinking ships and the impact of anchors.

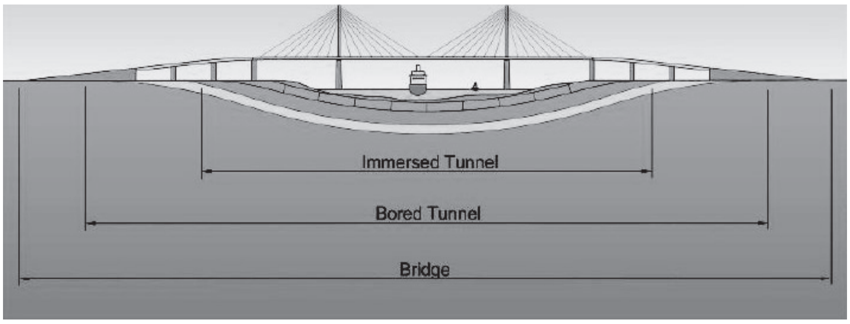
Objective. *The objective of the authors is to show advantages of immersed tube tunnels as compared to other technologies especially in the case of crossings below sea straits and under dangerous seismic conditions.*

Methods. *The authors use mathematical, engineering, comparative methods and analysis.*

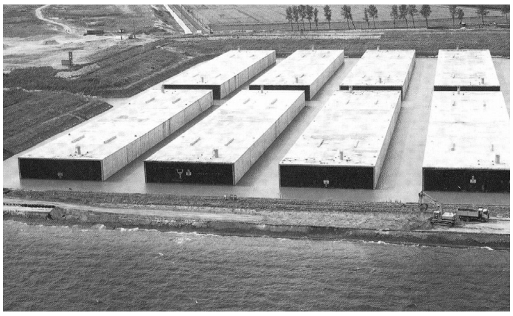
Results.

Advantages and disadvantages

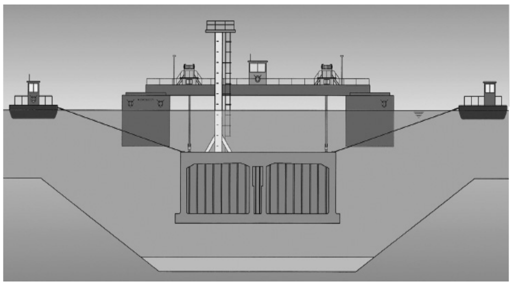
Over 100 immersed tube tunnels are in operation for different purposes with different cross-sections (Pic. 4 [1]) in the world now. They include road, railway tunnels, single-track and double-track tunnels, as well as tunnels for the simultaneous passage of trains and vehicles.



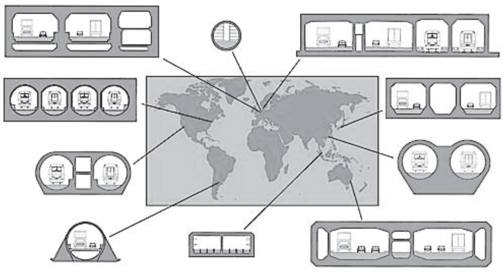
Pic. 1. Comparison of extension of transport passages across a water obstacle.



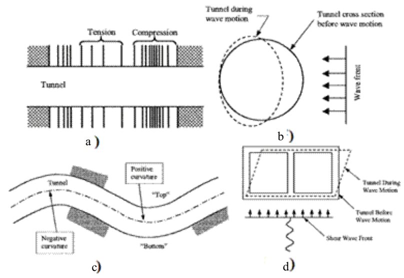
Pic. 2. Tunnel elements in dry dock.



Pic. 3. Mechanism of immersion of a tunnel section into a prearranged trench.



Pic. 4. Types of cross-sections of immersed tube tunnels and place of their construction.



Pic. 5. Possible deformations of tunnels under the influence of earthquakes [4].

Existing transport passages with immersed tube tunnels show benefits of such projects as compared with other types of passages.

1. All stages of construction are developed in detail: construction of sections, their transportation to the immersion site, methods of immersion.

2. Simultaneous production of a large number of sections on the shore and overlapping of stages of construction can significantly speed up the process of creating the tunnel.

3. Construction, which is running in the project area, has no effect on the local shipping.

4. Cross-section of the tunnel of concrete immersed tubes need not be cylindrical (as required by the shield tunneling), it is possible to construct tunnels with different cross-sectional shapes, and virtually all types of soils, including soft alluvial.

5. When using transport passages with such tunnels no limits are put on height or tonnage of vessels, so any additional organizational and technical difficulties are dismissed.

6. Immersed tube tunnels can be constructed in areas with high seismic activity with earthquake-resistant design.

7. Combined transport passage consisting of a bridge and immersed tube tunnel is more cost-effective as compared with options where a combination of a bridge with a shield tunnel is used.

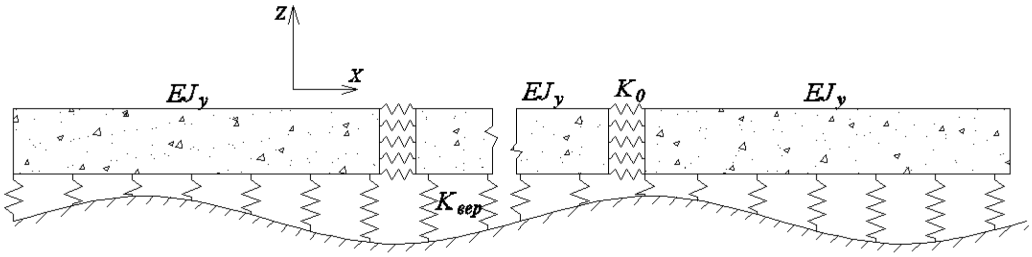
It should be noted that immersed tube tunnels have some disadvantages, which are mainly related to the impact on the environment, they can have a negative impact on fish inhabitation, change stream flows and reduce water clarity.

But the main drawback at the moment is the lack of experience in construction of this type of tunnels in the Russian Federation, the lack of necessary equipment. Nevertheless, it is time to break down the barriers: the country has a large number of water (sea and river) obstacles that require technically reliable transport passages, which do not violate well-established shipping routes.

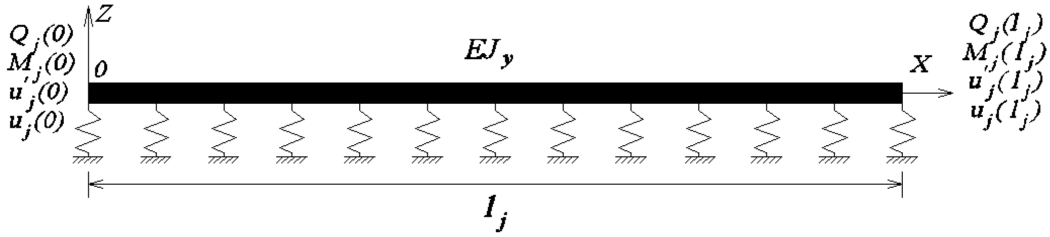
Methods of seismic effects calculation

In soft surface layers, where immersed tube tunnels are usually located, the intensity of seismic waves increases, so a resource for seismic stability should be provided at the design stage of structures for earthquake-prone areas. It is provided by methods of calculation used in the practice of tunneling [3,4].

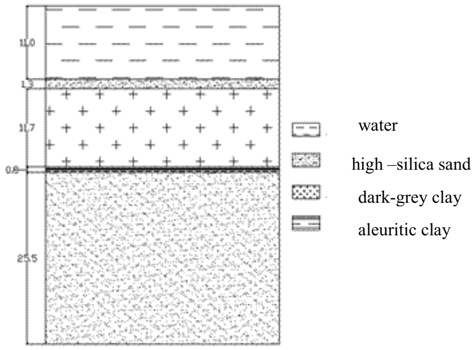
In the propagation of seismic longitudinal and transverse waves in a soil mass, where the tunnel is located, various types of deformation may occur. They are represented in Pic. 5. Deformations of tunnels on the background of longitudinal waves are shown in Pic. 5a and 5b; in case of transverse waves – in Pic. 5c (deflection of a tunnel) and 5d (shear deformation).



Pic. 6. Computational model.



Pic. 7. The local coordinate system of j-th element.



Pic. 8. Geologic profile of ground.

Usually the impact of longitudinal waves on the tunnels as compared with transverse waves is much lower.

Tensions in case of waves along the axis

The tunnel consists of separate beams on elastic foundation, connected by joints with elastic constraints, which are provided with rubber gaskets and cables for pretensioning [5]. The computational model is shown in Pic. 6.

To solve the problem, integral Fourier transform and generalized functions are used [6].

We divide the tunnel into n elements, for each one we use local coordinate system (Pic. 7).

Table 1

Characteristics of grounds

Material	Density (kg/m³)	Young modulus E (n/m²)	Poisson ratio ν
High-silica sand	1500	$0{,}12\times10^{9}$	0,3
Dark-grey clay	1600	$0{,}4\times10^{9}$	0,35
Aleuritic clay	1600	$0{,}65\times10^{9}$	0,35
Steel concrete	2500	$32{,}4\times10^{9}$	0,15

The differential equation of deflection of a beam on elastic foundation for j element [3] is:

$$EJ_y \frac{\partial^4 u_j}{\partial x^4} + Ku_j = Ku_g, \qquad (1)$$

where K is a coefficient of subgrade reaction of a foundation;

u_j – absolute displacement of tunnels;

$u_g = U_0 \sin(v_0 (x+L_j))\,(\theta(x) - \theta(x-l_j))$ – function of ground movement in the propagation of a transverse wave, presented in the form of a generalized finite function;

$\theta(x)$; $\theta(x-l_j)$ – Heaviside functions;

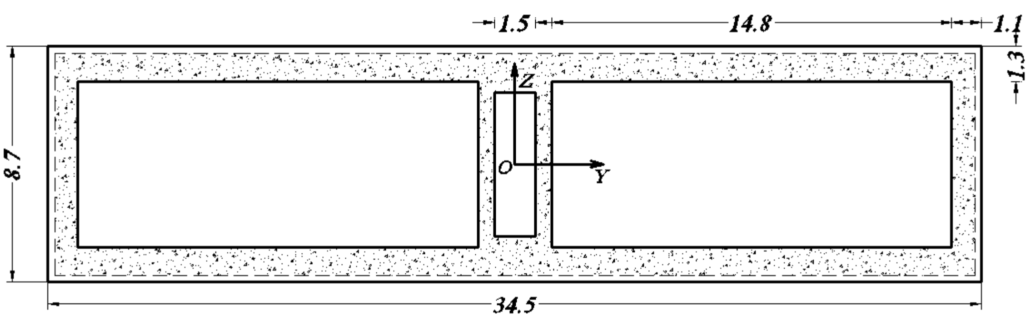
U_0 – peak value of movement of a soil mass at the location of the tunnel;

$v_0 = (2\pi f/C_s)$ – wave number, corresponding to a seismic wave with a dominant frequency f Hz;

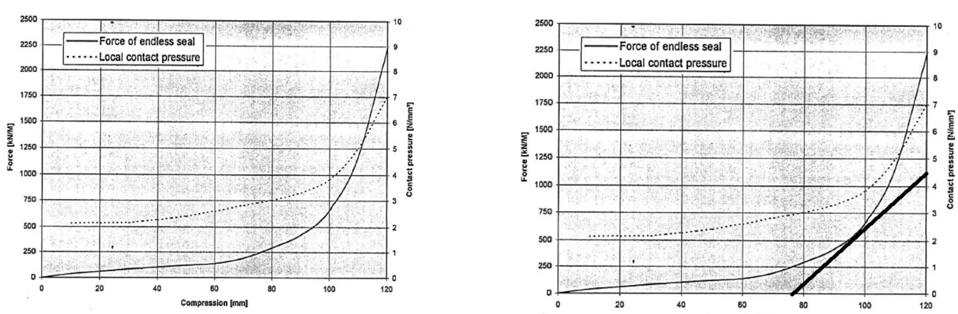
C_s – velocity of propagation of a transverse wave.

Applying the Fourier transform to both sides of equation (1), we obtain (2):

$$EJ_y\left(v^4+4\beta^4\right)\tilde{u}_j(v) = KU_0\left(\frac{e^{-iv_0L_j}\left(e^{i(v-v_0)l_j}-1\right)}{2(v-v_0)} - \frac{e^{iv_0L_j}\left(e^{i(v+v_0)l_j}-1\right)}{2(v+v_0)}\right) + Q_j(0) - e^{ivl_j}Q_j(l_j) -$$
$$-ivM_j(0) + ive^{ivl_j}M_j(l_j) - v^2u_j^{\cdot}(0)EJ_y + v^2e^{ivl_j}u_j^{\cdot}(l_j)EJ_y + iv^3u_j(0)EJ_y - iv^3e^{ivl_j}u_j(l_j)EJ_y. \qquad (2)$$



Pic. 9. Cross-section of the tunnel.



Pic. 10. Graph of relationship between load and compression of a rubber gasket (type ETS-180–220).

Table 2

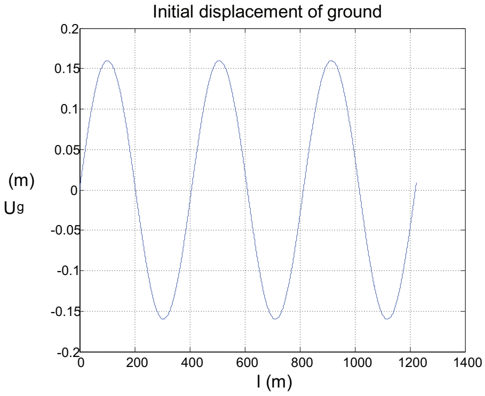
Maximum forces in the tunnel lining

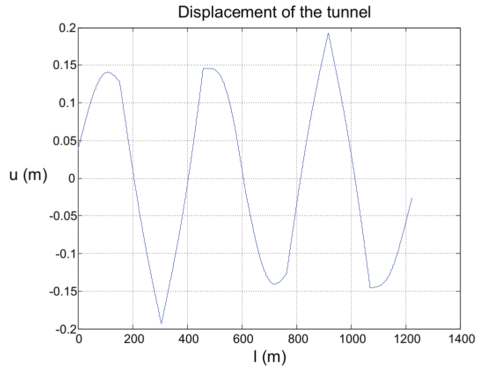
γ_{max} (*Rad*)	M_{max} (*kNm*)	Q_{max} (*kN*)
0,003	1,339e6	2818

Table 3

Force values in the section of the tunnel lining

Terms of calculation	N_{max} (*kN*)	M_{max} (*kNm*)	Q_{max} (*kN*)
Full sliding	2898	5328	1439
Without sliding	2889	5313	1435





Pic 11. Displacement of ground and cross-sections of the tunnel in the propagation of a transverse wave along the tunnel.

The equation (2) includes a function describing a given seismic impact, as well as eight parameters representing the value of deflection, angular deflection, moment and transverse force at the ends of section. We denote this part of the equation in terms of $\tilde{Q}_j(v)$. And so, the Fourier image of the function of deflection of the j-th element is given by:

$$\tilde{u}_j(v) = \frac{\tilde{Q}_j(v)}{EJ_y\left(v^4+4\beta^4\right)};\ j=1\div n, \quad (3)$$

where v is parameter of Fourier image;

$\tilde{u}_j(v)$ – Fourier image of the function $u_j(x)$;

$\tilde{Q}_j(v)$ – Fourier image of generalized load $Q_j(x)$;

$$4\beta^4 = \frac{K}{EJ_y}.$$

In accordance with the theorem of Paley-Wiener-Schwartz, function $\tilde{u}_j(v)$ must be integer, therefore the numerator, which is the sum of entire functions, contains zeros of the denominator. That is, for each section of the tunnel four conditions are in force:

$$\tilde{Q}_j(v_k) = 0, k = 1,2,3,4, \quad (4)$$

where v_k – roots of the expression $v^4+4\beta^4=0$.

Considering the conditions at the boundaries of extreme elements, as well as coupling of elements, it is possible to get a general system of algebraic equations, which allows us to determine values of parameters on the boundaries of the elements.

Solving the system of equations, we find the values of force and kinematic parameters on the boundaries of each section. Substituting the values found at the boundaries in the expression (3), we obtain the Fourier image of the function of deflection of each section of the tunnel. To determine the function of deflection, it is necessary to perform the inverse Fourier transform using the theory of residues.

Expression of the function of deflection for each section is obtained in explicit form. Because of the cumbersomeness of the expression, this formula is not given in the current paper. Knowing the expression of the function of deflection, we can determine internal forces in the section of the lining, necessary for the calculation of strength parameters.

In case of coupling of the sections of the tunnel it is necessary to take in account the hardness of rubbers between sections.

Example of calculation

As such, we use the characteristics of soils, corresponding to the conditions of Kerch Strait [7]. Cross-section of an undersea tunnel will be taken from the project [8], comprising eight sections, each 153 m long.

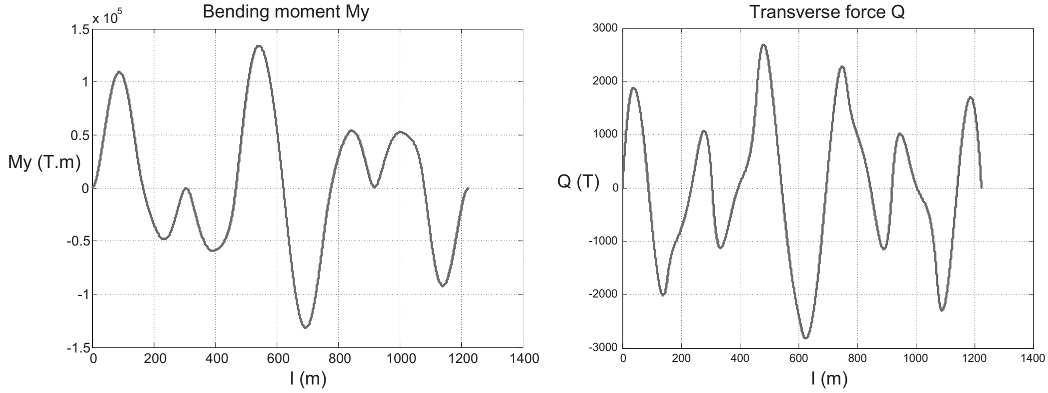
Kerch Strait is located in a region that has the highest seismic activity. There may be an earthquake with a magnitude of about 7.0, and the seismicity of 9 points and above. The values of peak acceleration, velocity and displacement in accordance with the data of Russian researchers (F. F. Aptikaev, N.N. Mikhailov [9]) are the following: PGA = 4 m / s^2; PGV = 0,55m / s; PGD = 0,2 m.

Characteristics of the cross-section are: H=8,7 m; B=34,5 m; L_{gasket}=84,4 m; $A_{cross\text{-}section}$=300,15 m^2; $A_{concrete}$=111,64 m^2; J_y=1314,7 m^4.

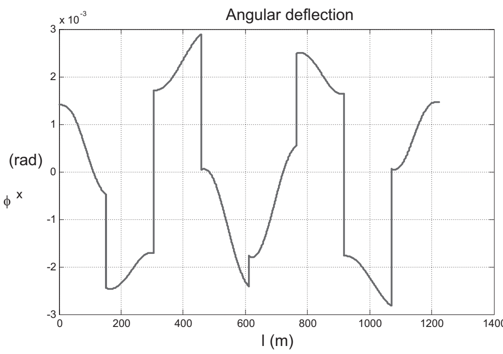
To connect sections of the tunnel between each other we will take into account rubber gaskets of ETS-180–220 type, which are applied in the tunnel Busan Geoje Fixed Link (South Korea) [10]. Dependence of force from displacement along the tunnel axis is shown in Pic. 10.

During installation of sections gaskets obtain initial shift. Initial compression force of gaskets depends on the average depth of the position of the tunnel (in this case it is 16, 5 m). From the basic data we can determine initial load on the rubber:

$$F_{initial} = \frac{\gamma_{wat}\times h\times A_{cross-section}}{L_{gasket}} = \frac{10\times 16{,}5\times 300{,}2}{84{,}4} = \frac{587\text{kN}}{\text{m}}.$$



Pic 12. Forces in tunnel lining



Pic. 13. Angular deflections of cross-sections of the tunnel lining.

Approximate initial compression of a rubber gasket is 9,7 cm.

Despite the fact that the behavior of gaskets «Gina» is essentially nonlinear, at the preliminary stage of calculation we can use solutions in the linear formulation. For this purpose, it is necessary to determine the initial compression, and tangent line, corresponding to it (Pic. 10).

Accordingly K_0=24,4e3 kN/m. Flexural rigidity of the connection between sections with a rubber gasket is given by:

$$K_f = H^2 K_0 \left(\frac{H}{3} + B \right) =$$

$$8,7^2 \times 24,44 \times 10^6 \times \left(\frac{8,7}{3} + 34,5 \right) = 6,9 \times 10^{10} \text{ N/m.}$$

Coefficient of subgrade reaction of a foundation in accordance with [12] is:

$$K = \frac{16\pi\mu_m(1-\nu)}{3-4\nu} \frac{H}{\lambda} =$$

$$\frac{16 \times 3,14 \times 0,063 \times 10^9 (1-0,35)}{(3-4\times 0,35)} \frac{8,7}{406,8} =$$

$$= 2,75 \times 10^7 \text{ N/m}^2,$$

where $\lambda = TC_s$=2x203,4=406,8 m is a dominant wave length.

The results of calculations are presented in graphical form in Pic. 11, 12.13.

The presented calculation method enables at the preliminary design stage to obtain internal forces, to design armature, to assess possible settlements and displacement of the tunnel lining.

Linings of rectangular cross sections

During earthquakes underground structures with sections of rectangular shape, which are located in soft or hard rocks, will suffer transverse deformations, which are similar in the form to the deformation of racks, because of shear deformations of the rock.

Taking into account that the main effect in the seismic impact on tunnels is ground deformation, displacement method will be the most convenient method of calculation.

To evaluate interaction of the tunnel lining with ground a simplified method [12] is used, which includes a series of operations.

1. We fix shear deformations of «free field» of the ground γ_{max} and $\Delta_{free\text{-}field}$ – difference between relative displacements of the top and the foundation of the cross-section of the tunnel:

$$\gamma_{max} = \frac{V_{peak}}{C_{ef}} = \frac{0,55 \times 0,8}{203,4} = 0,00216; \qquad (5)$$

$$\Delta_{free-field} = \gamma_{max} \times H = 8,7 \times 0,00216 = 0,0188 \text{ m.}$$

2. Stiffness is determined in the shear of box lining using the method of calculation of frame structures. Shear stiffness can be found by applying a unit force to the upper span, suggesting that the foundation is fixed, but with allowable rotations of joints. The ratio of the applied force to the resulting displacement helps to clarify the factor K_s (calculation scheme is shown in Pic. 14).

$$K_s = \frac{1}{Д} = \frac{1}{7,977e-6} = 125360,4 \text{ kN/m}^2.$$

3. Ratio of flexural rigidity of box structure is determined according to the formula:

$$F_r = \frac{G_m}{K_s} \frac{B}{H} = \frac{0,2567 \times 10^9 \times 34,5}{0,1254 \times 10^9 \times 8,7} = 8,117,$$

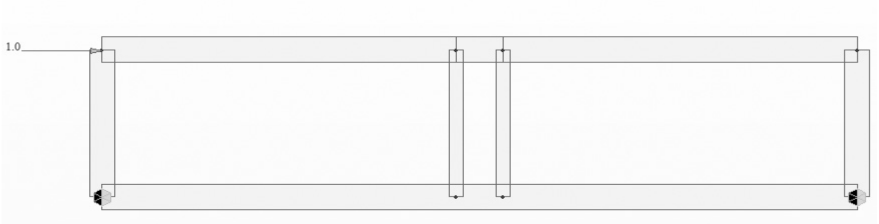
where H is height of cross-section of the lining;

G_m – mean deformation modulus of soil shear (at foundation and span of the tunnel levels), corresponding to the value of tension;

K_s – shear stiffness of the box structure of the lining.

4. Coefficient of shear stiffness R_r is determined for the construction under consideration. Coefficient R_r is a ratio of shear deformation of the structure Δ_s, located in the soil to the deformation of free field above the structure $\Delta_{free\text{-}field}$.

$$R_r = \frac{\Delta_s}{\Delta_{free-field}}. \qquad (6)$$



Pic. 14. Computational model.

Using the results of the studies presented in [12,13], shear stiffness coefficient can be determined by the formulas:

– In case of interaction without sliding of the tunnel lining in regard to the ground:

$$R_r = \frac{4(1-v_m)F_r}{3-4v_m+F_r} = \frac{4(1-0,48)\times 8,117}{3-4\times 0,48+8,117} = 1,8357; \quad (7)$$

– In case of interaction with full sliding of the tunnel lining in regard to the ground:

$$R_r = \frac{4(1-v_m)F_r}{2,5-3v_m+F_r} = \frac{4(1-0,48)\times 8,117}{2,5-3\times 0,48+8,117} = 1,84. \quad (8)$$

Using (5) – (8) we obtain shear deformations of the structure:

– in case of interaction without sliding:

$\Delta_s = R_r x \Delta_{free\text{-}field} = 1,835x0,0188 = 0,0345$ *m;*

– in case of interaction with full sliding:

$\Delta_s = R_r x \Delta_{free\text{-}field} = 1,84x0,0188 = 0,0346$ *m.*

Taking into account the obtained results and with the help of software package MIDAS CIVIL, we determine the internal forces in the section of the tunnel lining (Table 3).

Conclusion. *The analysis of constructed and projected traffic passages, in which immersed tube tunnels are used, shows that the selection of immersed tube tunnel project for a strait, as shown at example of Kerch Strait, can be the most cost-effective, reliable and affordable in terms of costs, time of construction and efficiency of technologies, which are applied.*

Tunnels are to a lesser extent exposed to seismic impact, since in them, in contrast to surface structures no resonance phenomena occur. With the passage of seismic waves they deform along with the surrounding ground mass, if it is solid, or they deform significantly less if the ground is soft. Those deformations are usually small and do not pose a serious danger to the tunnel lining. However, during strong earthquakes tunnels may be damaged.

A method was proposed for calculating the designs of immersed tube tunnels with account for seismic impact.

Keywords: *transport passage, water obstacles, tunnel, immersed tubes, beams on elastic foundation, Fourier transform, seismic impact, methods of calculation.*

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