Mechanics

Static Analysis of a Double-Chamber Tunnel Built Using Cut and Cover Construction

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ABSTRACT. The worldwide shortage of life and transport spaces makes it necessary to utilize underground space of the cities by construction of tunnels and near surface facilities using the so-called cut and cover method. Calculation of such structures is a responsible task. Now there are lots of numerical computer programs that are used in designing of the underground constructions. However, the numerical methods sometimes yield results that can vary significantly from those obtained with classical methods. Therefore, in some cases classical methods of forces and displacements are recommended to be used in the structural analysis of cut and cover tunnel structures. The concept is right not only for cut and cover, but for other types of tunnels and underground facilities. Tasks, which can be solved analytically, must be worked out by classical computer methods. The qualified specialists must use numerical methods in parallel with analytical methods, if possible. Such approach can be useful for facilitation of the work, testing the calculation results in order to avoid potential errors. It is often difficult to find the appropriate analytical apparatus for solving typical schemes of such structures. The analytical apparatus for static analysis of one or two-span frame of the tunnel structures using methods of forces and displacements is elaborated and presented in the paper. *© 2014 Bull. Georg. Natl. Acad. Sci.*

Key words: *underground structures, calculation.*

Underground facilities for transport, storages and other purposes are deepened up to 20 m. However, in special cases the depth may be much more [1]. Construction of the building may be presented by opened or closed frames with cast-in or built-up linear or curvilinear bearing elements and rigid joints. All joints are located along the centroids of the structural components. Elements are modeled as one meter wide segments in the longitudinal direction of the tunnel to represent a one-meter-wide slice of the structure. Calculated loads and load combinations are applied to the elements and joints. The structure is analyzed to determine internal and reactive forces, which will be used to design structural components of the tunnel. Design scheme of the reinforced concrete double-chamber tunnel structure is given in Fig.1.

As the tunnel is located completely underground it is subjected to loading on all the sides. The self weight load of the concrete structure and soil overburden as well as vehicular live loads (qv1) act in the vertical downward direction to the top slab. Lateral forces from live load, horizontal earth pressure and hydrostatic pressure act to the exterior walls in the form of trapezoidal epure (qh1, qh2). As it is known

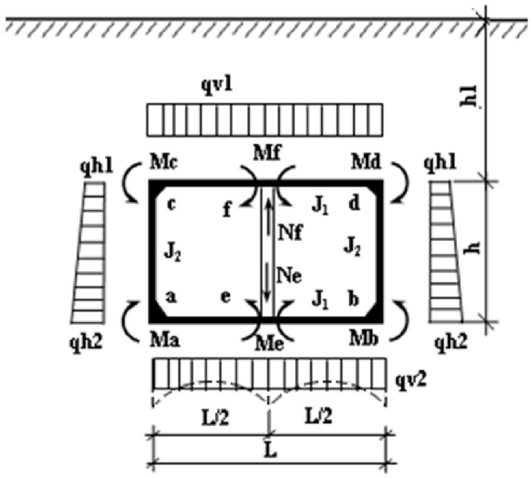

Fig. Design scheme of the reinforced concrete double-chamber tunnel structure

from Bases of Rock Mechanics, determination of these "active" loads for the cut and cover structures considered to be buried frame is not difficult. These load combinations are applicable for buried structures and denoted in Table 3.4.1-1 of the American Association of State Highway and Transportation Official (AASHTO) Specifications [1].

As to the bottom of the structure, presenting a plate on the elastic (deformable) foundation, it will be loaded by reactive vertical stresses (qv2), distribution character of which, generally speaking, depends on rigidness of frame-base system. Calculation of these stresses creates some difficulties and practical problems, related to determination of deformation parameters of the base. Therefore, reactive stresses on the bottom at the design scheme are often taken as uniformly distributed load of intensity equal to total weight of a one-meter-wide slice of the structure and overburden soil, divided on the width of the structure. Such simplification, as a rule, does not cause decrease of safety factor of the plate and the whole structure [2].

Such structures with rigid nodes and rectilinear rods are three and six times statically indeterminate systems for single-chamber and double-chamber cases, respectively. Hence, they are rather difficult analytical problems and it is impossible to find appropriate ready-made formulae. However, the numerical solution of this problem can be obtained by using a variety of commercial computer programs, which, as a rule, do not guarantee the accuracy of the calculations. For example, National Highway Institute of U.S. Department of Transportation considers [1] "it is recommended classical force and displacement methods to be used in the structural analysis of cut and cover tunnel structures. Other numerical methods may be used, but will rarely yield results that vary significantly from those obtained with the classical methods."

This understanding is right and timely not only for cut and cover, but for other types of tunnels [3] and not only tunnels. Tasks, which may be solved analytically, must be worked out by classical methods of Structural Mechanics using computers. But the qualified specialists must use computer programs of numerical methods in parallel with analytical methods for acceleration and facilitation of the work. Such approach may be useful for testing the calculation results and to avoid possible errors.

Below there are formulae for static calculation of the underground structure (Fig.), obtained by using classical methods of forces and displacement. For calculation of this statically undetermined structure it is necessary to consider materials, shapes and area of the cross sections of the elements in advance and specify those parameters in progressive approximation.

Consider elasticity modulus of structural materials as E; the areas and moments of inertia of the cross sections for top and bottom slabs, exterior and interior walls as: $F_t, I_1; F_b, I_1$; F_{ex}, I_2; and F_{in}, I_{in}, respectively. If we suppose that there is no interior wall, i.e. $F_{in} = I_{in} = N_f = N_e = 0$, the coefficient of relative rigidity of the one-chamber frame can be expressed as follows:

$$k = I_1 h / I_2 L. \qquad (1)$$

If the roof and walls are in articulated joints, the angles of rotations of their edges: $\theta_c(q_{v1})$ and $\theta_d(q_{v1})$, caused by the vertical loads only and manifested by yet undetermined bending moments

$M_c = -M_d$, can be expressed respectively [4]:

$$\theta_c(q_{v1}) = -\theta_d(q_{v1}) = \frac{q_{v1}L^3}{24EI_1}, \quad (2)$$

$$\theta_c(M_c) = \theta_d(M_d) = \frac{M_c(q_{v1})L}{3EI_1} + \frac{M_d(q_{v1})L}{6EI_1} = \frac{M_c(q_{v1})L}{2EI_1}. \quad (3)$$

Analogically, angles of rotations of exterior walls edges, caused by undetermined yet bending moments only, can be described as

$$\theta_a(M_a) = \theta_c(M_c) = \frac{M_c(q_{v1})h}{2EI_2} \quad (4)$$

and the condition of equality of angular deformations of the rigidly jointed edges of the walls and roof, will be expressed as

$$\frac{q_{v1}L^3}{24EI_1} + \frac{M_c(q_{v1})L}{2EI_1} = \frac{M_c(q_{v1})h}{2EI_2}, \quad (5)$$

from which nodal bending moments caused by the vertical loads only can be determined:

$$M_c(q_{v1}) = -M_d(q_{v1}) = \frac{q_{v1}L^2}{12}\frac{1}{1+k}. \quad (6)$$

Analogically, formulae of the same nodal bending moments, caused by the horizontal loads only on the external walls:

$$M_c(q_h) = -M_d(q_h) = \frac{(q_{h1}+q_{h2})h^2}{24}\frac{k}{1+k}. \quad (7)$$

Summing up (6) and (7) formulas for determination of bending moments caused by all active and reactive loads, for upper nodes *c* and *d* of the single-chamber tunnel will be obtained:

$$M_c = -M_d = \frac{1}{1+k}\left[\frac{q_{v1}L^2}{12} + \frac{(q_{h1}+q_{h2})h^2k}{24}\right]. \quad (8)$$

Hence, according to Structural Mechanics [4], the bending moment on the x section of the roof, in the absence of the internal wall and relative deflections in the middle points of roof and floor, will be, respectively:

$$M(x) = \frac{q_{v1}Lx}{2} - \frac{q_{v1}x^2}{2} - M_c, \quad (9)$$

$$y_{x=L/2} = \frac{L^2}{384EI_1}\left\{5q_{v1}L^2 - \frac{1}{1+k}\left[4q_{v1}L^2 + 2(q_{h1}+q_{h2})h^2k\right]\right\}. \quad (10)$$

Internal wall of the necessary rigidity and strength practically prevents relative deflections in the middle points of the tunnel's roof and floor as a result of appearance in them of reactive forces *Nf* and *Ne,* absolute values of which practically are mutually equal. Therefore, they can be determined according to condition of compensation of deflections (10).

Formula of S.Timoshenko [4] for establishing the relationship between efforts *Ne=Nf* and corresponding nodal moments in our notation has the form:

$$M_c(N_f) = -M_d(N_f) = \frac{N_f L}{8}\frac{1}{1+k}. \quad (11)$$

Hence, differential equation of deflected axis of the roof or floor, caused only by undetermined yet reactive forces in the internal wall will be expressed as follows:

$$EI_1\frac{d^2y}{dx^2} = \pm M(x) = \frac{N_f}{8}\left(\frac{L}{1+k} - 4x\right). \quad (12)$$

Because of the symmetry of the general scheme, at the integration of this equation the first coefficient is determined by condition of the absence of rotation over the interior wall (*section x=L/2*) and the second one – by the absence of deflections over the exterior walls (*x=0, L*). Consequently equation of deflected axis of the roof or floor in function of N_f will be:

$$y(x) = \frac{N_f}{4EI_1}\left(-\frac{x^3}{3} + \frac{Lx^2}{4(1+k)} + \frac{L^2}{4}\frac{kx}{1+k}\right), \quad (13)$$

and if we equate significance of (13) in the section *x=L/2* to (10), we establish required forces in the internal wall:

$$N_f = \frac{1+k}{L(1+4k)}\left\{2.5q_{v1}L^2 + \frac{1}{1+k}\left[2q_{v1}L^2 + (q_{h1}+q_{h2})h^2k\right]\right\}. \quad (14)$$

Now insertion (14) in the Timoshenko formula (11) and summing it to (8), expression for bending moments in the upper nodes of double-chamber tunnel, under all active and reactive loads will be obtained:

$$M_c = -M_d = \frac{1}{6(1+4k)}\left[2q_{v1}L^2 + (q_{h1}+q_{h2})h^2k\right] - \frac{5q_{v1}L^2}{16+64k}. \quad (15)$$

Same bending moments for lower nodes can be obtained by inserting qv2 instead of qv1 in (15). After nodal moments the further determination of span bending moments, longitudinal and lateral forces in other elements of tunnel using well-known apparatus of the Strength of Materials [4] presents no difficulty.

მექანიკა

ღია წესით გაყვანილი ორმალიანი გვირაბის სტატიკური გაანგარიშება

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აკადემიის წევრი, გ.წულუკიძის სამთო ინსტიტუტი, თბილისი

თანამედროვე ურბანიზაციის პირობებში საცხოვრებელი სივრცის დეფიციტის ინტენსიური და საყოველთაო ზრდა სულ უფრო აუცილებელს ხდის ზედაპირთან ახლოს განლაგებული მიწისქვეშა სივრცეების მაქსიმალურ ათვისებას მათში საყოფაცხოვრებო, სატრანსპორტო, სამრეწველო და მრავალი სხვა დანიშნულების ობიექტების განთავსებისათვის. მათი საიმედო დაპროექტება, უსაფრთხო და ეფექტური მშენებლობა საპასუხისმგებლო ამოცანას წარმოადგეს. სამუშაო სტიმულირებულია აშშ ტრანსპორტის დეპარტამენტის შოსე-გზების ნაციონალური ინსტიტუტის ტექნიკური სახელმძღვანელოთი, რომელშიც **(FHWA-NHI-10-034)** „ღია წესით" გაყვანილი გვირაბის გაანგარიშება რეკომენდებულია ჩატარებულ იქნას ძალთა და გადაადგილების მეთოდების გამოყენებით. შეიძლება გამოყენებულ იქნას აგრეთვე არსებული კომპიუტერული პროგრამები, მაგრამ ისინი ხანდახან იძლევიან მკაცრი ანალიზური გაანგარიშებებისაგან განსხვავებულ შედეგებს". სტატიაში განხილულია მიწის ზედაპირთან ახლოს ღია წესით გაყვანილი გვირაბის მუშაობა შემცველი ქანების და კონსტრუქციის საკუთარი წონით გამოწვეულ დატვირთვებზე. მოცემულია სწორხაზოვან ელემენტებიანი ორმალიანი ჩარჩოს სტატიკური გაანგარიშების ანალიზური აპარატი, მიღებული ძალთა და გადაადგილებების კლასიკური მეთოდებით.

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