STRUCTURAL ANALYSIS OF THE BUDAPEST-TYPE UNDERGROUND RAILWAY STATION

By

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Engineering structures in deep-trace underground railway lines — unless built in open excavation — are fully embedded in the rock or in the soil along their circumference. The soil and the tunnel structure are in close interaction, to be reckoned with in calculating tunnel wall stresses and deformations and in the structural analysis.

The prototype of the Budapest-type underground railway station has been developed for the Astoria station of the E—W line by designers of the UVATERV* [1], further developments being those of Kossuth Lajos tér, Batthyány tér and the stations of the first section of the N—S line [2, 3, 4, 5]. Twin tube is a typical cross section of these stations (Fig. 1). The tunnel structure made up of two intersecting circular cylinders is supported along the line of intersection by a vertical row of columns bearing on a cap and a sill beam.

The multiple applications of the Budapest type underground railway station, the technology and structural problems arisen in construction as well as further development possibilities — building mechanization, use of precast r.c. tunnel wall units, reduction of subsidences due to construction technology — motivated a detailed structural analysis beyond the scope of usual design calculations.

To this end, the method of "elastic soil lattice" [6] has been applied, involving the structural model shown in Fig. 2.

The following problems have been examined:

- effect of soil rigidity on the stresses and displacements of the structure;
- effect of the assumption of an active load on bending moments in the structure;
- response of the structure to an asymmetric active load;
- effect of soil bedding of the cap beam and of the type of the column joints — whether hinged or fixed — on the forces and reactions of the structure;

* Road and Railway Design Office

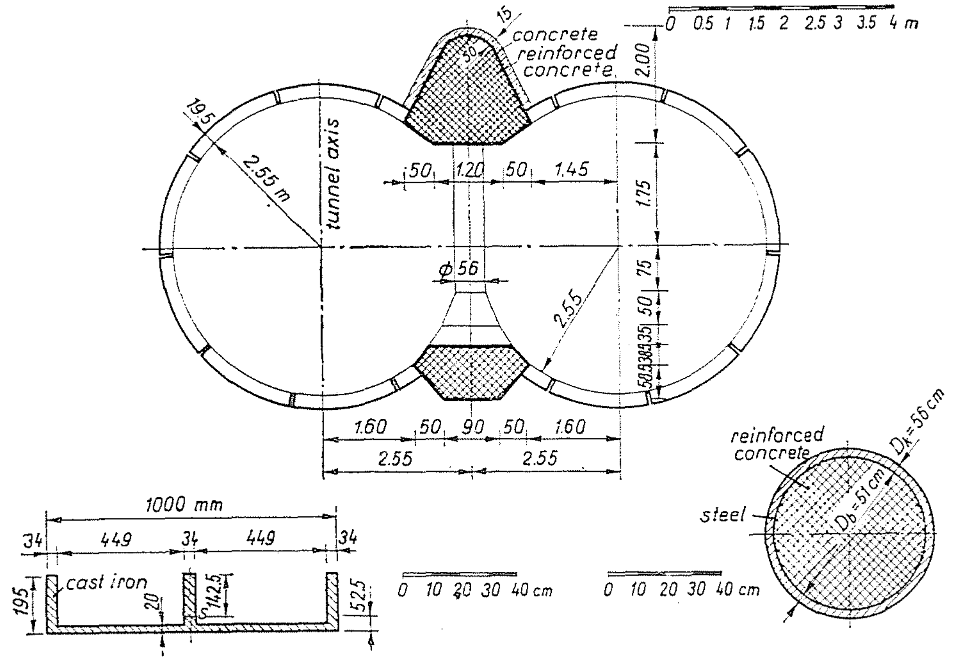

Fig. 1. Twin-tunnel cross section. Cross sections of tubbings K-2-L, Sz-2-L N-2-L. Column cross section. $F = 374$ cm², $K_{max} = 2456$, cm³, $K_{min} = 905$ cm³, $I = 12\,875$ cm⁴

— factors influencing the asymmetry of the bending moment diagram about the horizontal axis;

— structural behaviour of the twin tube lining composed of hinged precast r.c. units.

With increasing soil rigidity i.e. coefficient of subgrade reaction, maximum moments and displacements in the wall abruptly decrease up to $C = 10$—13 kp/cm³ while over these values the decrease is very small. Thus, for $C = 13$ kp/cm³ moments and displacements are practically independent of the variation in soil rigidity (Figs 3 and 4). This limit value of the coefficient of subgrade reaction decreases with the flexural stiffness of the structure. Normal forces little increase with the soil rigidity. The arch is bedded — i.e. displaced toward — the soil over greater lengths in rigid soils, and over lesser lengths in less rigid soils. In soils with low coefficient of subgrade reaction where bedding stresses only develop at the cost of great deformations of the tunnel wall, great bending moments develop also at the bottom section of the structure (Fig. 5), and the moment distribution in a symmetric structure tends to a moment diagram symmetric about the horizontal axis.

Distribution of the active load over the wall greatly affects moments in the structure.

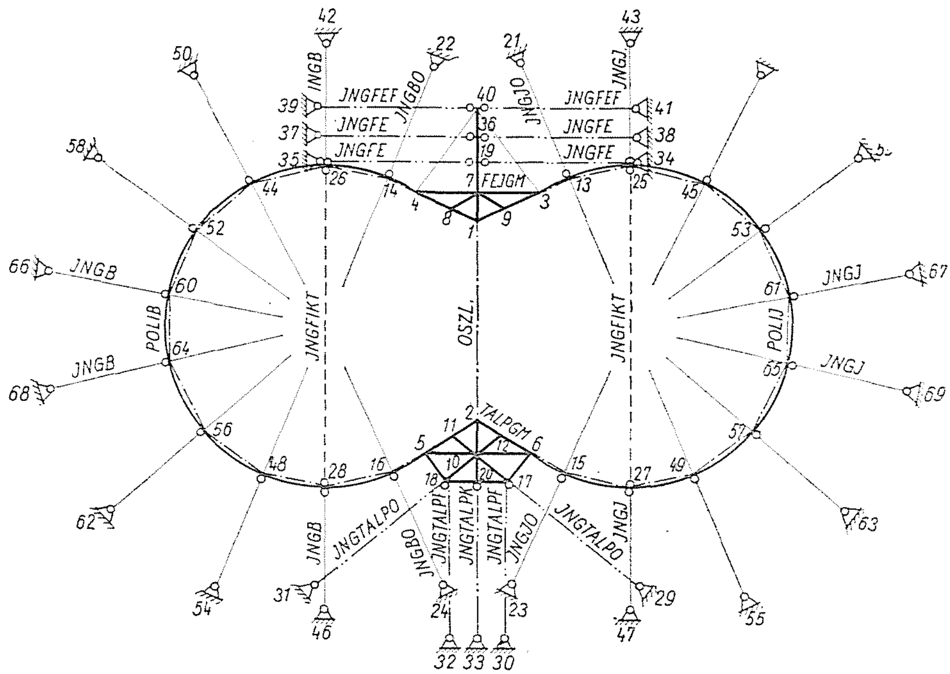

Fig. 2. Structural model of the twin-tunnel cross section of the Budapest-type underground railway station. Remarks: 1. Bars 25—27 and 26—28 INGFIKT with zero bending and compressive rigidities have been applied to ease computer running; 2. Bars crossing in the model are intersecting only if their nodes are numbered

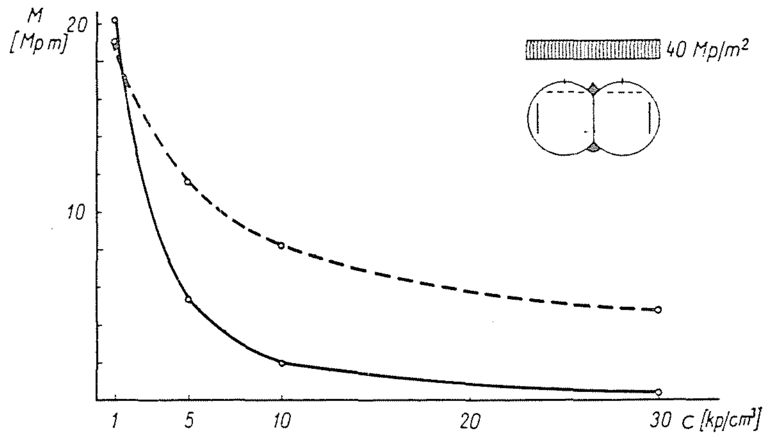

Fig. 3. Roof and springing moments in twin tunnels vs. coefficient of subgrade reaction. - - - - roof moment; ——— moment in the horizontal section

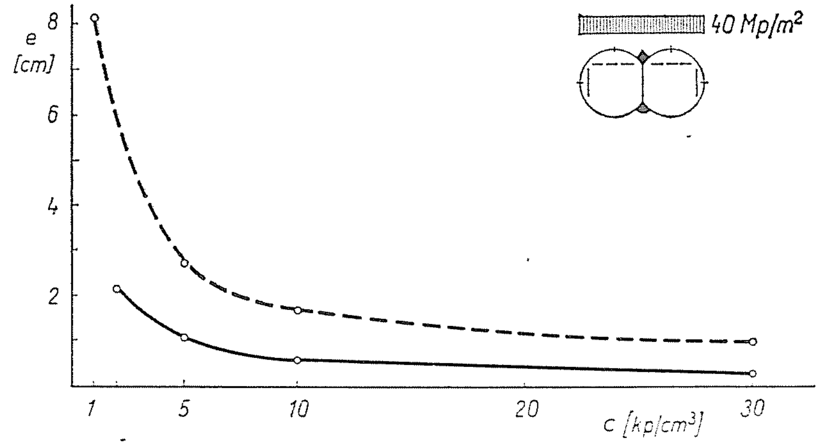

Fig. 4. Vertical and horizontal displacements of the roof and horizontal axis points of a twin tunnel vs. coefficient of subgrade reaction; – – – – – vertical displacement of roof point, ——— horizontal displacement of horizontal axis point

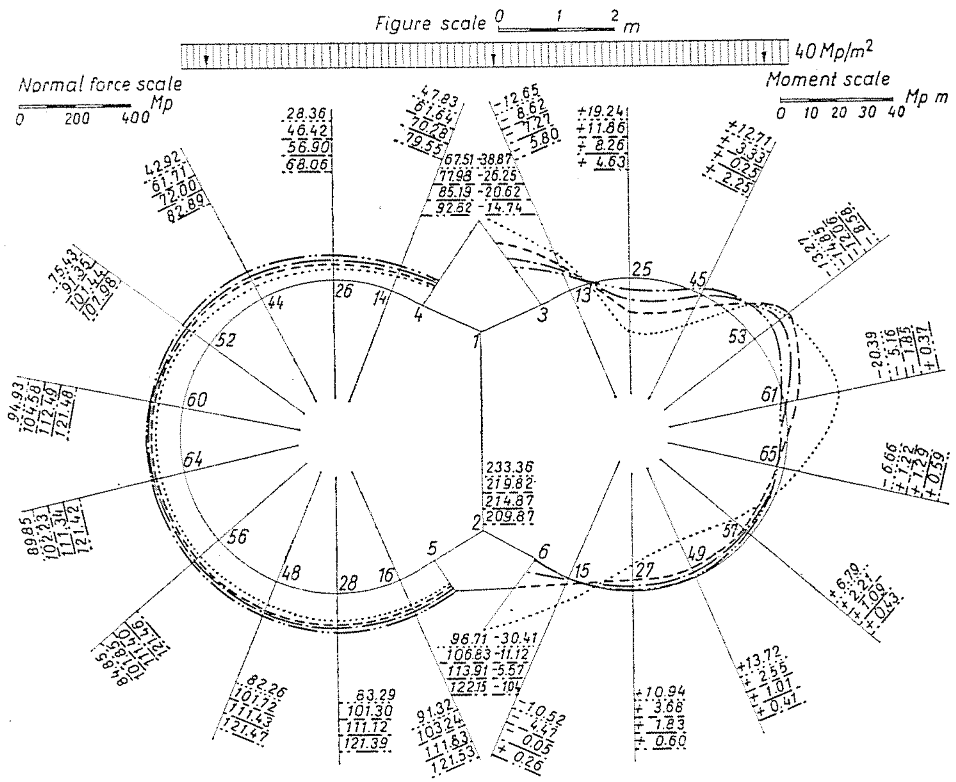

Fig. 5. Normal force and bending moment diagrams for the cross section of a twin tunnel subject to 40 Mp/m² uniform vertical active load for four different bedding coefficients. ...... c = 1 kp/cm³; – – – – c = 5 kp/cm³; –·–·–l c = 10 kp/cm³; –··–··– c = 30 kp/cm³

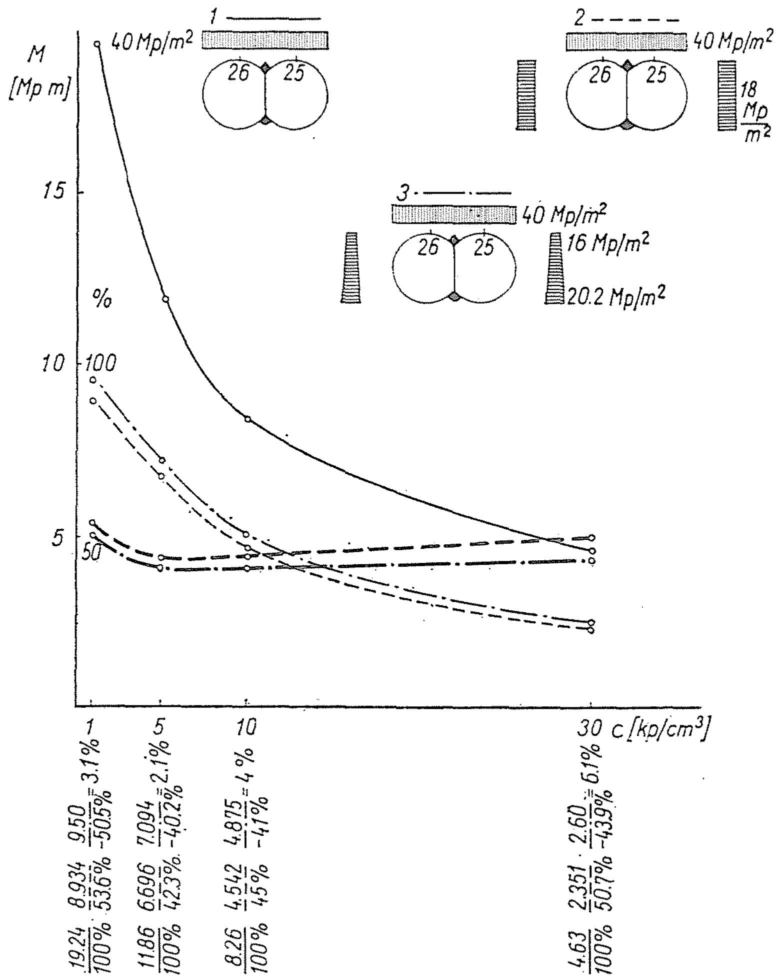

Fig. 6. Maximum positive moment of twin tunnels vs. coefficient of subgrade reaction and distribution of active loads. - - - - - ΔM1—2 = moments in loading case 2 as percentages of case 1; —·—·—·— ΔM 1—3 = moments in loading case 3 as percentages of case 1

By active load is meant the earth pressure acting on the structure immediately after its being built in. In wall sections displaced toward the cavity, its value is assumed to be constant, while in wall sections displaced toward the soil, its value is assumed to be increased by the bedding reaction.

The maximum positive moment developing in the wall roof is halved — practically regardless of the coefficient of subgrade reaction — if about 50% of the vertical active load acts as a horizontal active load on the wall (load cases 1 and 2 in Fig. 6). Consideration of the dead weight of the soil or rock mass entrains a variation of only 3 to 6% in the moment values (load

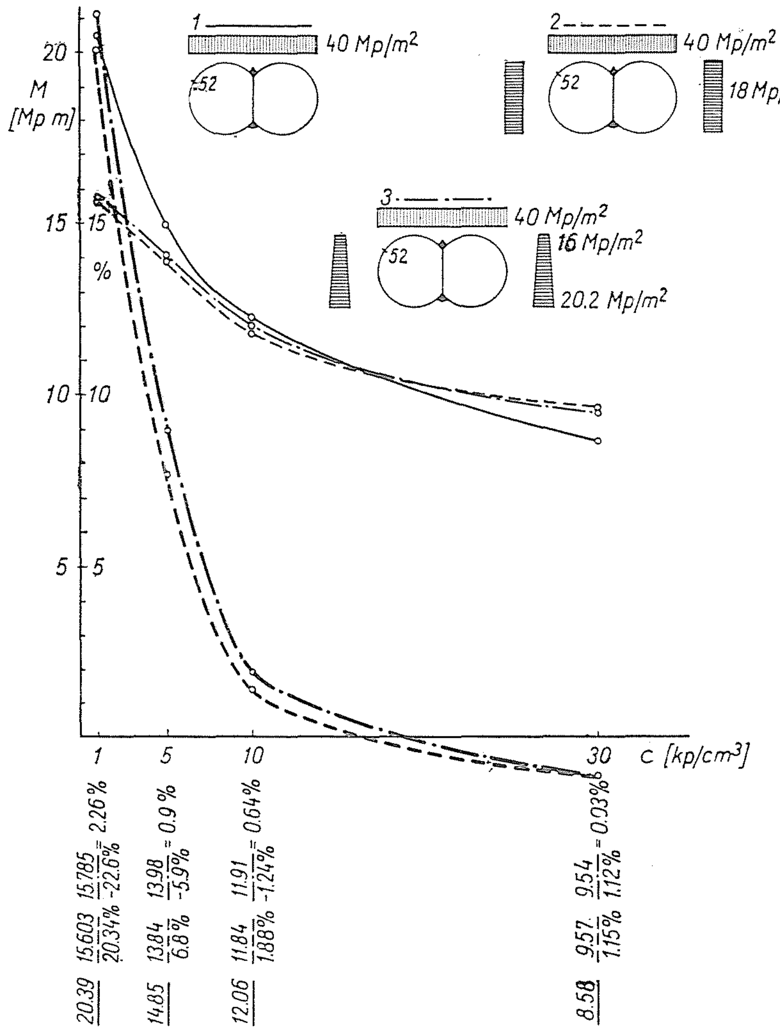

Fig. 7. Maximum negative moment of twin tunnels vs. coefficient of subgrade reaction and distribution of active load. —·—·—·— ΔM 1—3 = moments in loading case as percentages of case 1; – – – – ΔM 1—3 = moments in loading case 3 as percentages of case 1

cases 2 and 3 in Fig. 6). The 50% horizontal working load causes a change as little as 1 to 5% in the maximum negative field moment value, while consideration of the effect of gravity forces in the half-space modifies the moment by as little as about 0.5% (Fig. 7).

A lesser or greater asymmetry of the active load about the vertical axis has always to be reckoned with, due to soil inhomogeneities and the non-simultaneous construction of symmetric parts of the tunnel structure.

Asymmetry due to active load is evidenced by field measurements made by UVATERV on columns in the cross section of the five-tunnel station.

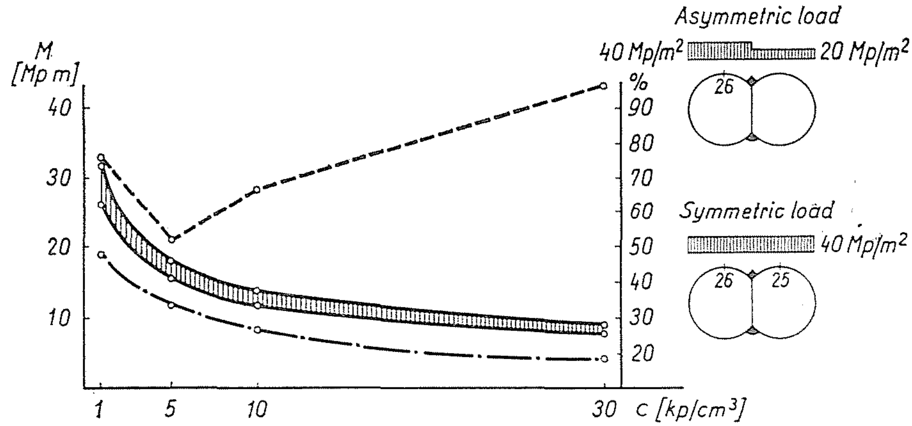

Fig. 8. Positive roof moments vs. load, structural design and coefficient of subgrade reaction

Legend for Figs 8 and 9: –·–·–·– symmetric load; ▥ asymmetric load with different structural solutions (hinged or clamped columns, reckoning with or neglecting soil bedding of sill and cap beams; — — — — — — moment increment as a percentage of symmetric moments. Diagrams have been plotted from moment values belonging to coefficients of subgrade reaction $\delta = 1$; 5; 10; 30 kp/cm

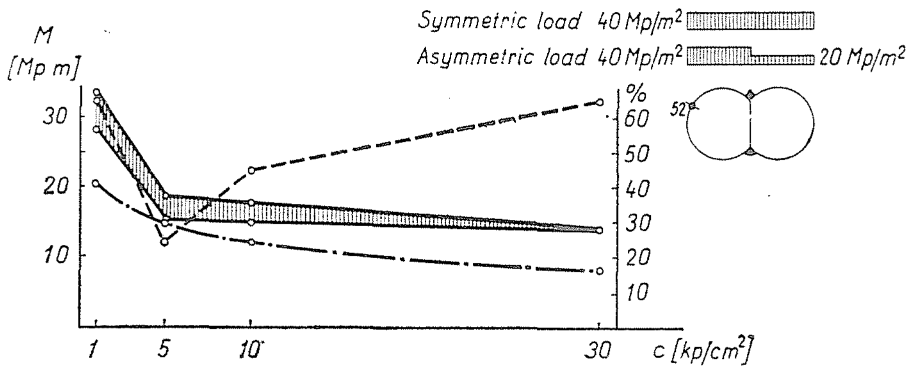

Fig. 9. Negative moments at point 52 vs. load, structural design and coefficient of subgrade reaction

Our analyses assumed active loads to be quite asymmetric. Thereby consequences of asymmetry can clearly be stated. Depending on the coefficient of subgrade reaction, 50% asymmetry in the vertical active load increases the maximum positive roof bending moment by 20 to 45%, and the maximum negative field moment by 10 to 30% (Figs 8 and 9).

In the case of an asymmetry in the vertical active load of about 50% the vertical displacement of the top increases by 50 to 80% depending on the structure — whether supported by hinged or fixed-end columns —, on the degree of soil bedding of cap and sill beam (Fig. 10). This effect is insignificant at the springing point (point 60 of the structural model) for both the vertical and the horizontal displacements. In the horizontal axis point, the subgrade

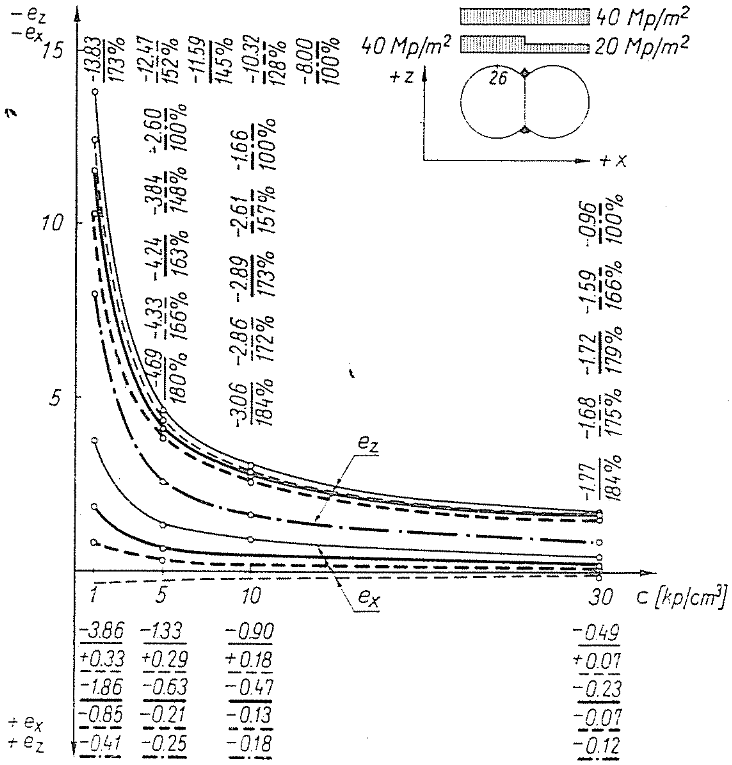

Fig. 10. Horizontal and vertical displacements e_x and e_z of the roof point of a twin tunnel vs. active load asymmetry, soil rigidity and structural design. Legend: ——— horizontal and vertical displacements with hinged column and omitting soil bedding; – – – – horizontal and vertical displacements with hinged column and soil bedding; ——— horizontal and vertical displacements with clamped column and omitting soil bedding; – – – – horizontal and vertical displacements with clamped column and soil bedding; –·–·–·– vertical displacements due to symmetric load. Remarks: 1. Vertical displacement e_z is given as a percentage of that due to symmetric load. 2. Soil bedding refers to sill and cap beam

reaction value is little affected by an asymmetric load on the wall ring above which the active load is constant, while above the ring where the active load is halved, also the subgrade reaction decreases by 10 to 20%, depending on the structural design (Fig. 11).

Subgrade stresses are fairly uniform at the base (points 27 and 28 of the model) and they are but slightly lower than those due to symmetric active loads.

An asymmetric load reduces the normal forces in the springing point (points 60 and 61 of the structural model) by about 20% in the less loaded ring, while in that with the higher load, normal forces will be about equal to those due to symmetric loads (Fig. 12). Soil bedding of the cap and the sill beam and a hinged or clamped mode of column connection are practically irrelevant for stresses and displacements of the tunnel wall, as seen from dia-

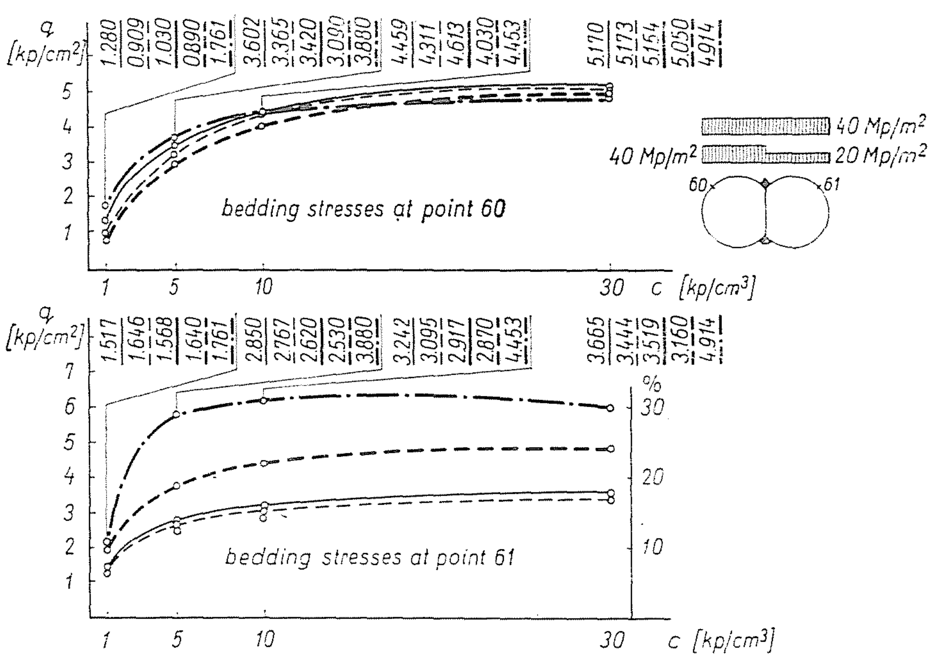

Fig. 11. Bedding reaction stress due to asymmetric load vs. coefficient subgrade reaction at points 60 and 61 symmetric about the twin tunnel column axis; ——— hinged column omitting soil bedding; - - - - hinged column with soil bedding; ——— clamped column omitting soil bedding; - - - - clamped column with soil bedding; —·—·—· bedding stresses due to symmetric load at points 60 and 61. Bedding stress decreases at point 61 as a percentage of the symmetric stress. Remark: Soil bedding refers to sill and cap beam

grams in Fig. 8 where the max. roof moment, the most sensitive to these effects, has been plotted vs. the coefficient of subgrade reaction. Moment values obtained for the examined structural varieties are inside the narrow shaded area.

Soil bedding of cap and sill beam reduces the deflection from the vertical of the columns especially in the case of hinged columns (Fig. 13).

Rigid connections between the column and the cap and sill beam induce important column moments without relieving other structural parts. Column moment values are affected by the bedding of cap and sill beam, reducing the rotation and deflection of the column. Variation of the moment at the base of the column is seen in Fig. 14.

The diagram of moments in the twin-tunnel wall structure nearly symmetrical about the horizontal axis due to a uniform vertical load will be asymmetrical about the horizontal axis. The same refers to elastically bedded circular arches.

Factors and their influence on the asymmetry of the moment diagram about the horizontal axis for twin tunnels have been examined and compiled

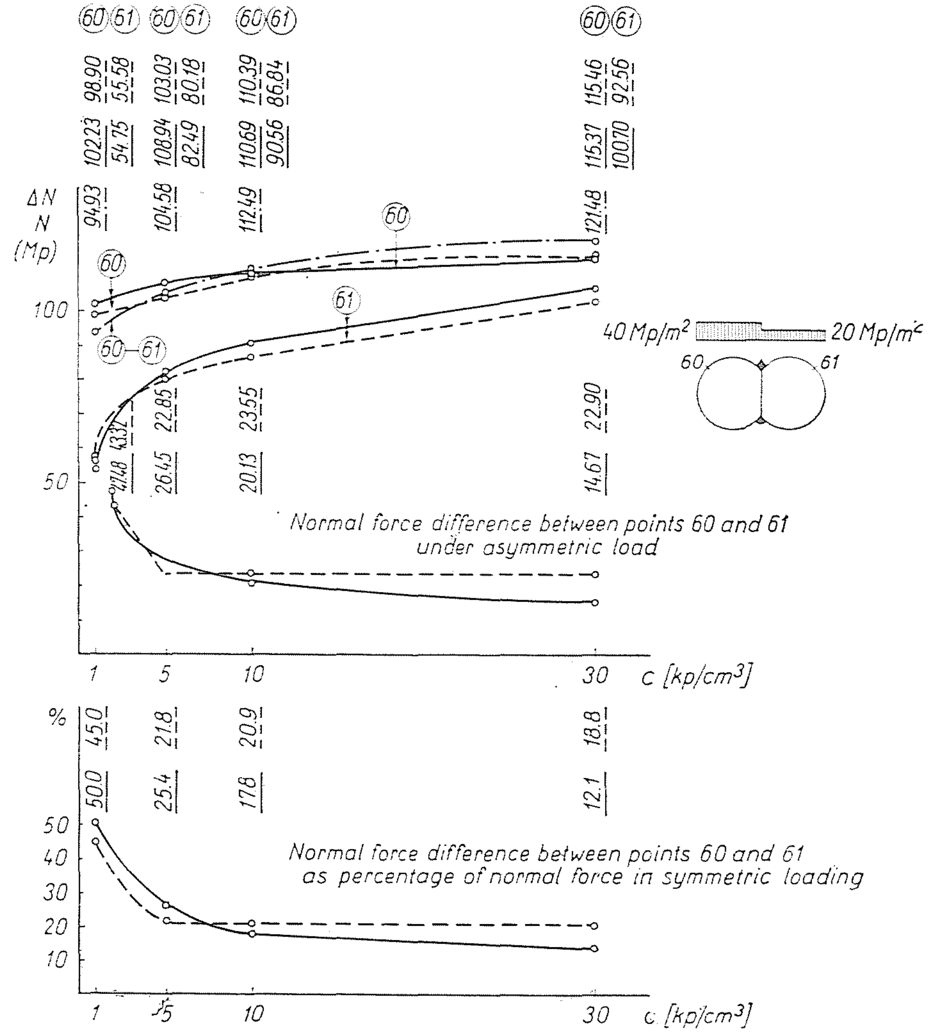

Fig. 12. Normal forces in hinged columns due to asymmetric load vs. coefficient of subgrade reaction at points 60 and 61 symmetric about the twin tunnel column axis: – – – – normal force and difference of normal forces for soil-embedded sill and cap beam (asymmetric load); ——— normal force and difference of normal forces omitting soil bedding of cap and sill beam (asymmetric load); –·–·–·– normal force due to symmetric load at points 60 and 61

in Fig. 15. 4.3% of the difference between roof and base moments were found to be due to structural asymmetry, 35% to the asymmetry of the vertical active load about the vertical axis, 53.4% to the asymmetry of the soil to tunnel wall connection about the horizontal axis and 7.3% to the asymmetry of the horizontal active load due to the dead weight of the soil in the semi-space.

These percentages show an eventual small-scale model to depend more on the correct simulation of gravity forces in the semi-space than on that of the

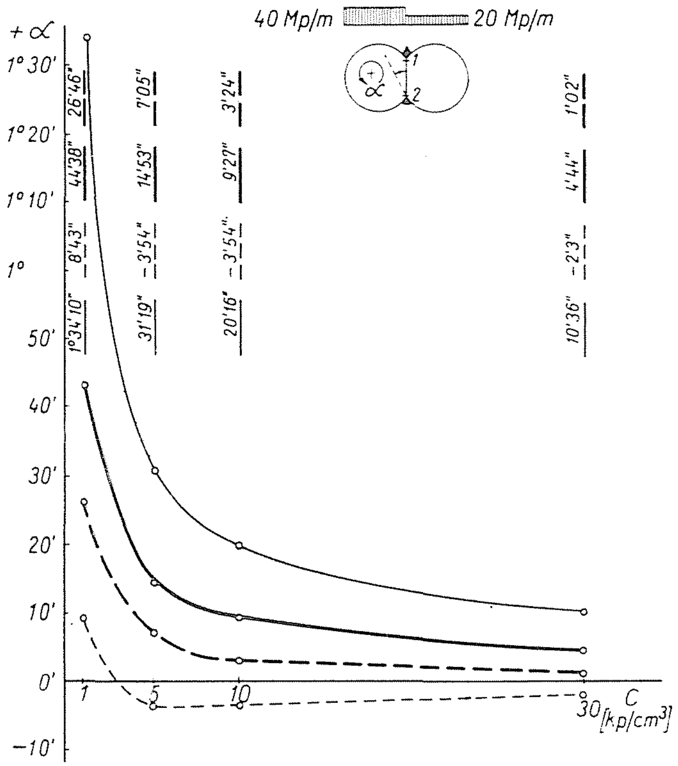

Fig. 13. Deflection from the vertical of the column axis between points 1 and 2 as a function of coefficient of subgrade reaction and structural design: – – – – soil-embedded hinged column; ——— hinged column omitting soil bedding; – – – – clamped column with soil bedding; ——— clamped column omitting soil bedding. Remark: 1. α values have been computed from displacements of points 1 and 2; 2. soil bedding refers to cap and sill beam

development of the active load and of the mode of soil to wall connection. The same is true for finite-element mathematical models of semi-space.

These statements of the structural analysis refer to continuous twin-tunnel wall structures i.e. those with flexural rigidity. Requirements to develop more advanced station structures, to mechanize the construction, to reduce site labour demand coupled with the rising world market price of steel suggest this station type to be constructed of precast r.c. units — as are line tunnels. Inherent rigidity of precast r.c. tunnnel walls is significantly lower. A hinge joint between precast units entrains instability of the wall without adequate soil support, stressing the importance of soil bedding for the stability, deformation and stresses in this structure type. Hence, an asymmetric structure without satisfactory soil bedding of the sill beam and the cap beam or a tunnel wall made up of hinged units and acted upon by an asymmetric vertical active load will be unstable. This instability can be offset by rigid connection of column to cap beam or by soil bedding of both sill and cap beams. In the

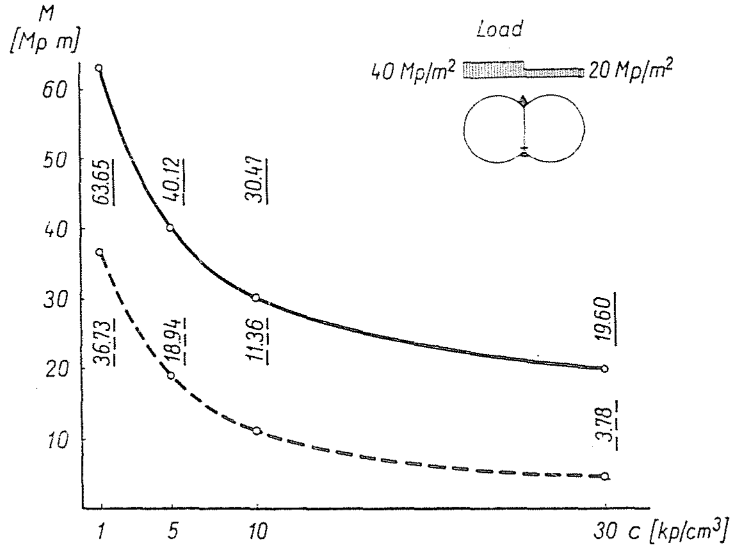

Fig. 14. Bending moments due to asymmetric active load in the column base fixed in the sill beam of the twin tunnel: – – – – considering soil bedding of cap and sill beam; ——— omitting soil bedding of cap and sill beam. Remark: Indicated stresses refer to one meter running of tunnel. Their four-fold develops in columns spaced at four meters

five-tunnel station, vaults spanning between column rows and consisting of more than two hinged units will only be stable if at the bottom of the units forming a three-hinged arch, adequate soil bedding is provided.

For the Budapest-type underground station it can be concluded that with respect to stresses, displacements and stability during and after construction of the station, the surrounding soil is of decisive importance both for the development of working loads, and for the stability and load capacity of the station structure. Hence in structural design, in planning the building technology, and in structural analysis, the soil to structure interaction has to be reckoned with. This statement is even more valid for the case where the inherent flexural rigidity of the tunnel wall is reduced further by the application of precast r.c. units.

Summary

Behaviour of the structure of the Budapest-type Underground Station has been analyzed by the "elastic soil lattice" method. Stresses, displacements and stability of the tunnel wall are influenced by soil rigidity, mode and asymmetry of working load, soil bedding of sill and cap beam, hinged or clamped column connections. Factors and their influence on the bending moment diagram asymmetry about the horizontal axis are examined for symmetric active loads.

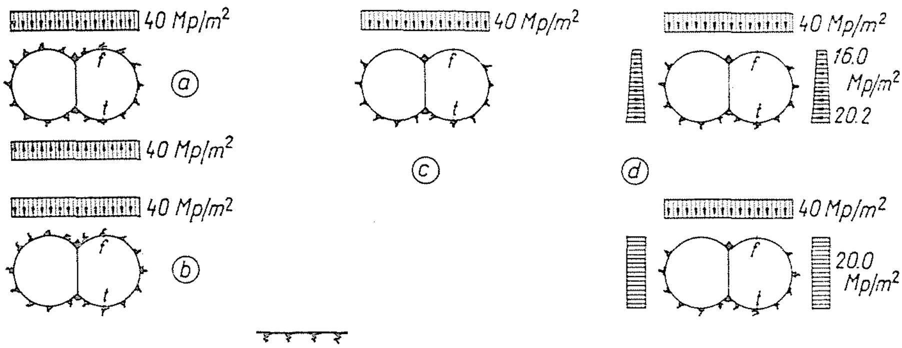

Fig. 15. Effect of factors causing asymmetry of twin tunnel moment diagrams about the horizontal axis, in terms of difference between roof and base moments (coefficient of subgrade reaction $c = 10$ kp/cm³): *a.* effect of structural asymmetry connection between soil and wall assumed to be equivalent in tension and compression; *b.* asymmetry of vertical active load about the horizontal axis; *c.* asymmetry of soil to tunnel wall connection about the horizontal axis; *d.* asymmetry of horizontal active load about the horizontal axis. Sum of bending moment differences:

$M_f = 2.651$ Mpm
$M_t = 2.328$ Mpm
$\Delta M_1 = 0.323$ Mpm 4.3%

$M_f = 3.780$ Mpm
$M_t = 1.2395$ Mpm
$\Delta M_2 = 2.55$ Mpm 35%

$M_f = 8.2619$ Mpm
$M_t = 1.8331$ Mpm
$\Delta M' = 6.4288$ Mpm
$\Delta M_3 = 3.88$ Mpm 53.4%
$M_f = 4.8751$ Mpm
$M_t = 0.661$ Mpm
$\Delta M = 4.269$ Mpm
$M_f = 4.5419$
$M_t = 0.7990$
$\Delta M = 3.7429$
$\Delta M = \Delta M' - \Delta M''$

$\Delta M_4 = 0.534$ Mpm 7.3%
$\Delta M\Sigma = 7.267$ Mpm 100%

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* In Hungarian