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ELECTROMAGNETIC FIELD OF COAXIAL LINES WITH AXIAL SLIT IN A TUNNEL, IN AN ENCLOSED BRIDGE OR IN A MINE PIT

This paper is dedicated to Professor Jovan Surutka on the occasion of his 80th birthday

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Abstract: Using equivalent electrodes method the distribution of electromagnetic field of coaxial line in one and double track tunnel, bridge and mine pit is determined, when a train is in it or when it is vacant and numerous graphical results for equipotential and equienergetic curves are presented.

Key words: Coaxial line, electromagnetic field, radio link, equivalent electrodes method.

1. Introduction

Directional antennas set at the ends of the tunnel, or slit coaxial lines drawn through the tunnel or along the bridge are used for realizing a radio link space-time continuum between a locomotive and a dispatcher center, in the case of the train is in the tunnel or in the enclosed steel bridge (Tunnels and bridges are then behaving as hollow waveguides with low frequencies bandstops.). Consequently, slit coaxial lines as well as shielded lines with rectangular slit shields have been an object of several investigations [1]-[7]. The equivalent electrodes method, which has been developed at the Faculty of Electronic Engineering in Niš, proved as a very useful method for solving lines with slit shields [8]. This method is also applied for determining the electromagnetic field which slit coaxial lines produce in tunnels and in

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bridges with one or double track. For thus purpose, it is adopted that the progressive TEM waves propagate on the slit coaxial line alone, assuming the tunnel walls, train and earth surface perfectly conductive. The calculations are based on the equivalent electrodes method, considering the influence of the train and tunnel on the slit line and conversely. A developed program package TUNNEL [9] provides a variety of possibilities for the users. Above all it is the possibility of a true setting of the size and shape of the train, and the shape of the walls of tunnel or bridge. As a result of the calculation the values for characteristic impedance and resistance per unit line length of the coax with axial slit are obtained. The values for potential and electric and magnetic field strengths in a prescribed region of interest are also obtained. Map of equipotential curves, as well as of equienergetic curves, defining a geometric position of the points of constant intensity of the electric and magnetic field strength, or of constant densities of the energies located in the field, can also be obtained. Numerical results for equipotential and equienergetic surfaces in the case of one and double track tunnels and bridges, when they are vacant or when a train is in them, or trains cross over them, are presented in this paper. The quite similar procedure is used for analyzing electromagnetic field distribution of coaxial line in a mine pit, with and without train in it.

2. Short Theoretical Approach

The aim of this paper is to determine the electromagnetic field distribution in a tunnel, bridge, or mine pit, when a train is in it or when it is vacant. Because an exact analytical solution does not exist, the equivalent electrodes method, as very simple and exact, is used for approximate numerical solving the presented problems.

2.1 About equivalent electrodes method

Some time ago first author suggested a new numerical method, so-called the **equivalent electrodes method** (EEM), for non dynamic electromagnetic fields and other potential fields of theoretical physics solving. The first very good results were obtained in Ref.10, when the method was used for calculating the equivalent radius of uniform antennas. Afterwards, the good results were obtained in the computations of electrostatic fields [12]-[14], in the theory of low-frequency grounding systems [15], in the static magnetic field solving [16], [17] and for transmission lines analysis [18], [19]. Also, the method was extended to other potential fields: to heat flow problems [20] and for plan-parallel fluid flow solving [21]. The basic idea of the proposed theory is: an arbitrary shaped electrode can be replaced by a finite system of **equivalent electrodes** (EE). Thus it is possible to reduce a large number of complicated problems to equivalent simple systems. Depending on the problem geometry, the flat or oval strips (for plan-parallel fields) and spherical bodies (for three-dimensional fields), or toroidal electrodes (for systems with axial symmetry) can be commonly used. In contrast to the charge simulation method [22], when the fictitious sources are placed inside the electrodes volume, the EE are located on the body surface. The radius of the EE is equal to the equivalent radius of electrode part which is substituted. Also the potential and charge of the EE and of the real electrode part are equal. So it is possible, using boundary condition that the electrode is equipotential, to form a system of linear equations, with charges of the EE as unknowns. By solving this system, the unknown charges of the EE can be determined and, then, the necessary calculations can be based on the standard procedures. It is convenient to use Green's functions for some electrode, or for stratified medium, in case when the system has several electrodes, or when the multilayer medium exists, and after the remaining electrodes to substitute by EE. In the formal mathematical presentations, the proposed EEM is similar to the moment method form [23], but very important difference is in the physical fundaments and in the process of matrix establishments. So it is very significant to notice that in the application of the EEM an integration of any kind is not necessary. In the moment method solutions the numerical integration is always present, which produces some problems in the numerical solving of nonelementar integrals having singular subintegral functions.

2.2 Mathematical model of tunnel, bridge, or mine pit and the EEM application

In order to use EEM first the mathematical model of the tunnel, bridge, or mine pit with built-in coaxial line with axial slit has been derived. There, the plan-parallel cylindrical cavity with quite arbitrary, but known cross section is considered. The cavity walls, as well as the earth surface and train are assumed to be perfectly conductive (Fig. 1). The coaxial line with axial slit is placed at the top of the tunnel. Radius of its interior conductor is a, of shield is b and the angular width of the shield slit is 2α The walls of the tunnel and train, as well as the interior conductor of coaxial line and its shield, are replaced by a cage system of EE (Fig. 2(a)). A magnified part 1234 is shown in Fig. 2(b).

These equivalent electrodes represent the flat and oval strip elements of

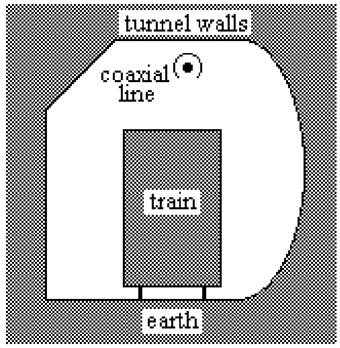
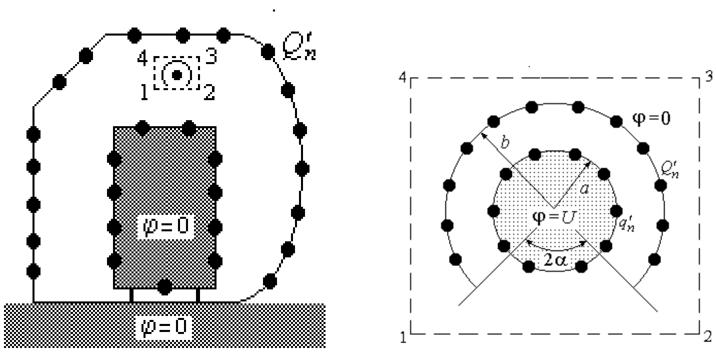


Fig. 1. Cross section of conducting cavity representing mathematical model.



(a) (b)

Fig. 2. Cage system of EE.

large length and neglectable width. As it is shown in [8], the flat strip of large length and neglectable width can be replaced by a cylindrical conductor of circular cross section having a radius equal to the equivalent radius of the strip,

$$a_{\mathrm{e}} = \frac{d}{4}, \tag{1}$$

where d denotes the strip length. The axis of this equivalent conductor coincides with a mean derivation of the flat strip. The equivalent radius in the case of the oval strip, having radius a and angular width 2α, is

$$a_{\mathrm{e}} = a \sin\left(\frac{\alpha}{2}\right). \tag{2}$$

The axis of this equivalent conductor also coincides with a mean derivation of the oval strip. The potential, after the influence of earth surface is taken into account by EE images in relation to the flat mirror coinciding with the earth surface, can be expressed in the form

$$\varphi = \sum_{n=1}^{N} q_n' G(\boldsymbol{r}, \boldsymbol{r}_n) + \sum_{n=1}^{M} Q_n' G(\boldsymbol{r}, \boldsymbol{r}_n), \tag{3}$$

where $q_n', n = 1, 2, \dots, N$ is the line charge per unit length of N EE representing the interior conductor of slit line and Q_n', $n = 1, 2, \dots, M$ is the line charge per unit length of M EE representing the line shield, train and tunnel walls;

$$G(\boldsymbol{r}, \boldsymbol{r}_n) = \frac{1}{2\pi\varepsilon_0} \ln \frac{\left|\boldsymbol{r} - \boldsymbol{r}_n'\right|}{\left|\boldsymbol{r} - \boldsymbol{r}_n\right|} \tag{4}$$

is the Green's function for potential of the EE and its image in the flat mirror; $\boldsymbol{r}$ is the field point position vector; $\boldsymbol{r}_n$ is the position vector of the electrical middle point of the EE; $\boldsymbol{r}_n'$ is the position vector of the electrical middle point of the EE images; and ε_0 is the electrical permittivity of air.

Therefore, a number of unknown quantities having to be determined is

$$K = N + M. \tag{5}$$

The potential of the interior conductor of slit line is U.

Using the condition that the EE have the same potential as the interior conductor they represent, N equations are obtained

$$\begin{aligned} 2\pi\varepsilon_0 U = &\sum_{n=1}^{N} q_n' \ln \frac{\left|\boldsymbol{r}_m - \boldsymbol{r}_n'\right|}{\sqrt{\left|\boldsymbol{r}_m - \boldsymbol{r}_n\right|^2 + \delta_{nm} a_{\mathrm{en}}^2}} \\ &+ \sum_{n=1}^{M} Q_n' \ln \frac{\left|\boldsymbol{r}_m - \boldsymbol{r}_n'\right|}{\sqrt{\left|\boldsymbol{r}_m - \boldsymbol{r}_n\right|^2 + \delta_{nm} a_{\mathrm{en}}^2}}, \quad m = 1, 2, \dots, N. \end{aligned} \tag{6}$$

The potential of the tunnel walls, train and shield of the slit line is zero. Using the condition that the EE have the same potential as the tunnel walls, train and shield they represent, M additional equations are obtained

$$\begin{gathered}\sum_{n=1}^{N} q_n' \ln \frac{\left|\boldsymbol{r}_m - \boldsymbol{r}_n'\right|}{\sqrt{\left|\boldsymbol{r}_m - \boldsymbol{r}_n\right|^2 + \delta_{nm} a_{\text{en}}^2}} \\ + \sum_{n=1}^{M} Q_n' \ln \frac{\left|\boldsymbol{r}_m - \boldsymbol{r}_n'\right|}{\sqrt{\left|\boldsymbol{r}_m - \boldsymbol{r}_n\right|^2 + \delta_{nm} a_{\text{en}}^2}} = 0, \\ m = N+1, N+2, \ldots, N+M = K. \end{gathered} \tag{7}$$

In these equations a_{en} is the radius of EE and δ_{nm} is Kronecker's symbol.

After solving the linear equations (6) and (7) and determining the unknown line charges per unit length of EE, the capacitance per unit slit line length can be expressed as

$$C' = \frac{q'}{U}, \tag{8}$$

where

$$q' = \sum_{n=1}^{N} q_n' \tag{9}$$

is the total charge per unit interior conductor of slit line length.

Further, the characteristic impedance of slit line is calculated as

$$Z_c = \frac{\sqrt{\varepsilon_0 \mu_0}}{C'}, \tag{10}$$

where μ_0 is the magnetic permeability of air.

The vectors of the electric and magnetic field strength have only transversal components and can be presented in the form

$$\boldsymbol{E} = \boldsymbol{E}_0 e^{-\gamma z} \tag{11}$$

and

$$\boldsymbol{H} = \boldsymbol{H}_0 e^{-\gamma z}, \tag{12}$$

where γ is the propagation constant of the slit line and the $z-$ axis is along the tunnel.

$\boldsymbol{E}_0$ and $\boldsymbol{H}_0$ are given by

$$\boldsymbol{E}_0 = -\text{grad}\varphi = \sum_{n=1}^{N} q_n' \boldsymbol{G}(\boldsymbol{r}, \boldsymbol{r}_n) + \sum_{n=1}^{M} Q_n' \boldsymbol{G}(\boldsymbol{r}, \boldsymbol{r}_n) \tag{13}$$

and

$$\boldsymbol{H}_0 = \sqrt{\frac{\varepsilon_0}{\mu_0}} \boldsymbol{E}_0 \times \hat{z}, \tag{14}$$

where

$$\boldsymbol{G}(\boldsymbol{r}, \boldsymbol{r}_n) = -\text{grad}G(\boldsymbol{r}, \boldsymbol{r}_n) = \frac{1}{2\pi\varepsilon_0}\left(\frac{\boldsymbol{r}-\boldsymbol{r}_n}{\left|\boldsymbol{r}-\boldsymbol{r}_n\right|^2} - \frac{\boldsymbol{r}-\boldsymbol{r}_n'}{\left|\boldsymbol{r}-\boldsymbol{r}_n'\right|^2}\right) \tag{15}$$

and where $\hat{z}$ is the unit vector associated to the z-axis.

Calculations show that the influences of tunnel or bridge, as well as train in tunnel, or in bridge, can be neglected when the characteristic impedance of coaxial line with axial slit is determined. The values for the characteristic impedance of the single coaxial line with axial slit when the ratio b/a is different, the angular width of shield slit is different and the shield thickness is negligible are presented in Table 1. These results show that larger slits of the shield correspond to bigger values of the characteristic impedance. The bigger ratio of shield and interior conductor radii, b/a, the higher characteristic impedance.

Table 1. Characteristic impedance $Z_c[\Omega]$ of the air coax with axial slit of neglectable shield thickness, for different ratio b/a and different angular width of shield slit, α.

$\alpha[^0]$	$b/a=2$	$b/a=3$	$b/a=4$	$b/a=5$
0	41.589	65.917	83.178	96.586
5	41.646	65.974	83.235	96.623
15	42.095	66.430	83.692	97.081
25	42.967	67.337	84.607	98.000
35	44.224	68.690	85.986	99.388
45	45.848	70.492	87.838	101.261
55	47.839	72.756	90.185	103.644
65	50.221	75.512	93.063	106.577
75	53.047	78.814	96.527	110.116
85	56.359	82.742	100.660	114.344
95	60.382	87.417	105.581	119.379
105	65.180	93.010	111.458	125.390
115	71.043	99.776	118.540	132.619
125	78.361	108.099	127.204	141.438
135	87.766	118.593	138.047	152.438
145	100.369	132.326	152.119	166.656
155	118.385	151.425	171.516	186.180
165	147.372	181.302	201.620	216.375
175	212.364	246.817	267.257	282.062

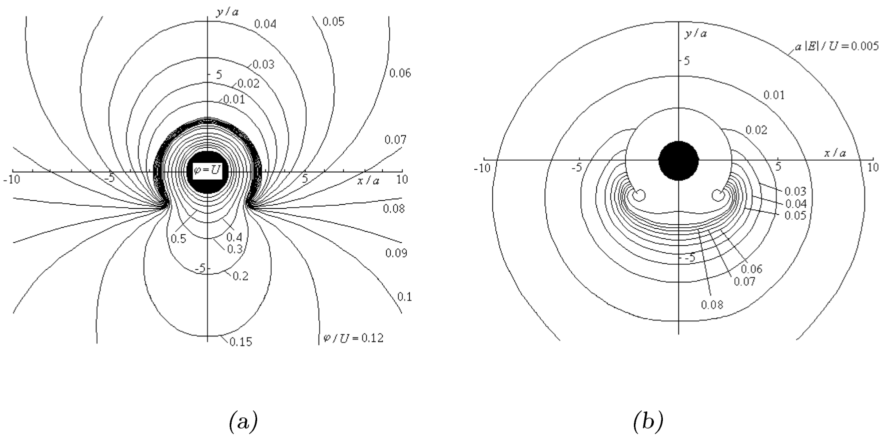


Fig. 3. Equipotential (a) and eqienergetic (b) curves of the single coaxial line with axial slit.

Equipotential curves of the single coaxial line with axial slit are shown in Fig. 3(a) in the case of $b/a = \mathrm{e}$ and $\alpha = 50^0$. There, the potential of the shield is considered to be zero, and of the interior conductor to be equal to U.

Equienergetic curves for single coaxial line with axial slit of mentioned dimensions are shown in Fig. 3(b), on which volume density of the energy located in the electric, apropos magnetic field is constant, and intensities of the electric, E_0, and magnetic, H_0, field strength are here constant.

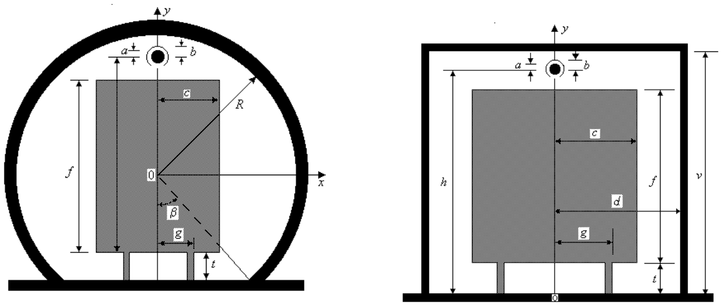
3. Numerical Results

3.1 One track tunnels and bridges

Numerical results presented in this chapter refer to the coaxial line with axial slit having ratio of shield and interior conductor radii, $b/a = 2$, and angular width of slit, $2\alpha = 100^0$ The considered tunnels and bridges (Fig. 4) have dimensions given in Table 2.

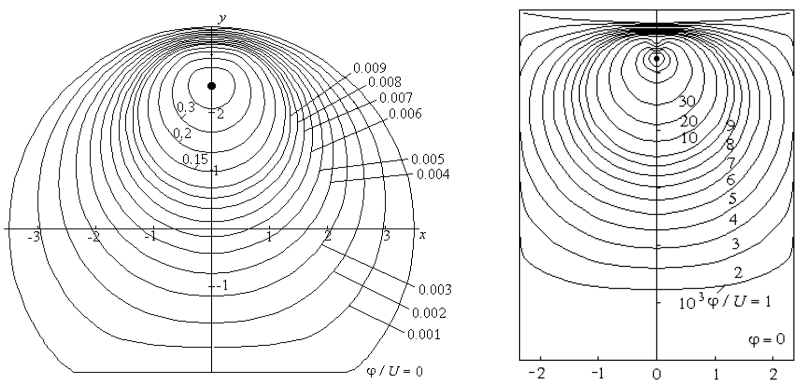
Table 2. Dimensions of tunnel and bridge (Fig. 4).

$b/a = \mathrm{e}$	$v/a = 600$	$d/a = 225$
$\alpha = 50^0$	$h/a = 530$	$f/a = 345$
$g/a = 75$	$t/a = 150$	$c/a = 150$



(a) (b)

Fig. 4. One track tunnel (a) and one track bridge (b), when a train is in it.



(a) (b)

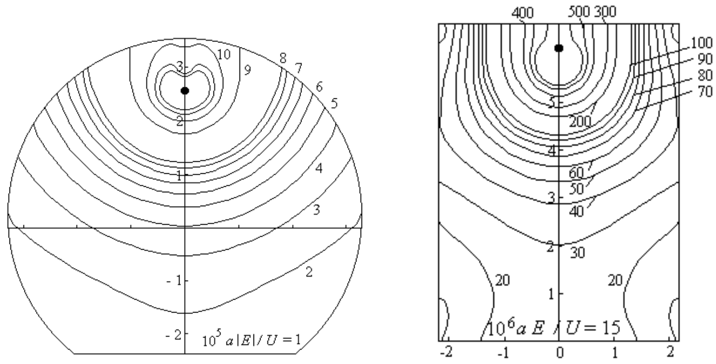
Fig. 5. Equipotential curves of the coax with axial slit in the vacant tunnel (a) and in the vacant bridge (b).

Equipotential surfaces of the coax with axial slit in the vacant one track tunnel, or bridge are shown in Fig. 5.

Equienergetic surfaces of the coax with axial slit in the vacant one track tunnel, apropos bridge are shown in Fig. 6.

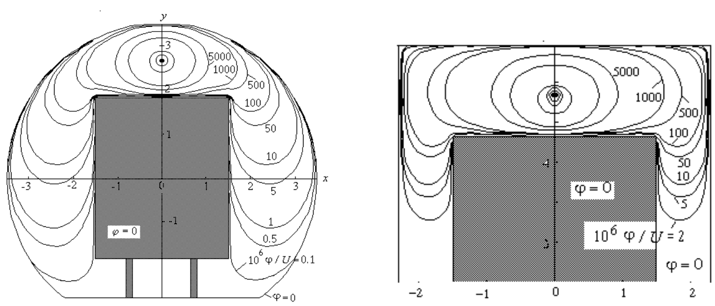
Equipotential surfaces of the coaxial line with axial slit in one track tunnel, or bridge when a train is in it, are shown in Fig. 7.

Equienergetic surfaces of the coax with axial slit in the one track tunnel, apropos bridge when a train is in it, are shown in Fig. 8.



(a) (b)

Fig. 6. Equienergetic surfaces of the coax with axial slit in the vacant tunnel (a) and in the vacant bridge (b).



(a) (b)

Fig. 7. Equipotential curves of the coax with axial slit in the tunnel (a) and in the bridge (b), when a train is in it.

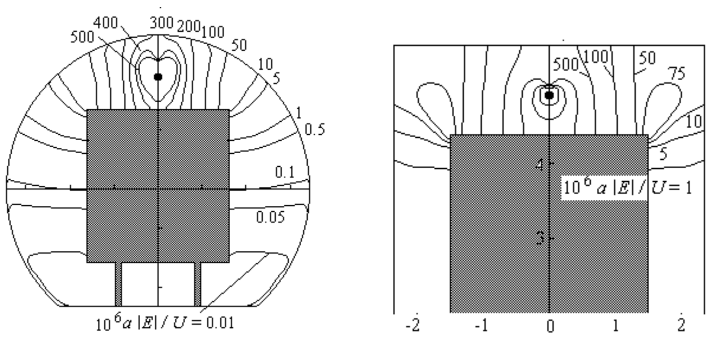
3.2 Double track tunnels and bridges

The considered tunnels, or bridges, have dimensions given in Tables 3 and 4.

Table 3. Dimensions of double track tunnel (Fig. 9).

$b/a = 2$	$v/a = 900$	$d/a = 325$
$\alpha = 45^0$	$u/a = 200$	$R/a = 500$
$g/a = 600$	$t/a = 120$	$c/a = 390$

The geometry of the double track tunnel, apropos bridge when a train is in it, or when trains cross over in it, is shown in Fig. 9 and 10.

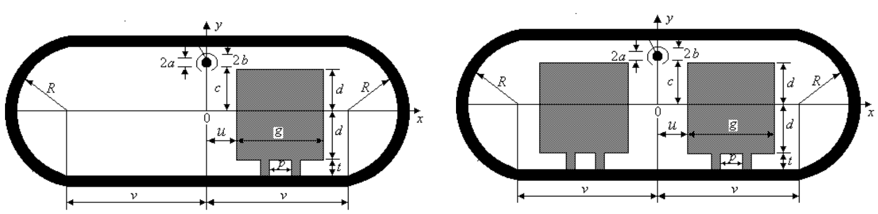


a) b)

Fig. 8. Equienergetic surfaces of the coax with axial slit in the tunnel a) and in the bridge b), when a train is in it.

Table 4. Dimensions of double track bridge (Fig. 10).

$b/a = 2$	$v/a = 1100$	$h/a = 1000$
$\alpha = 45^0$	$u/a = 200$	$d/a = 325$
$g/a = 600$	$t/a = 120$	$c/a = 390$



(a) (b)

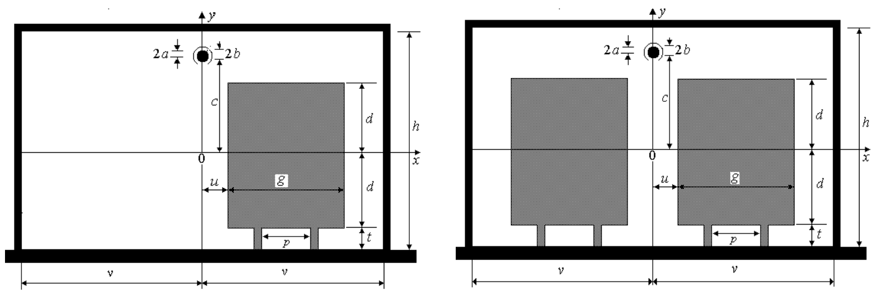
Fig. 9. Mathematical model of tunnel when a train is in it (a) and when two trains (b) are in it.

Equipotential surfaces of the coaxial line with axial slit in the double track tunnel, or bridge when it is vacant, or when one train is in it or two trains are in it, are shown in Fig. 11 and 12.

Equienergetic surfaces of the coax with axial slit in the double track tunnel, apropos bridge when it is vacant, or when one train is in it or two trains are in it, are shown in Fig. 13 and 14.

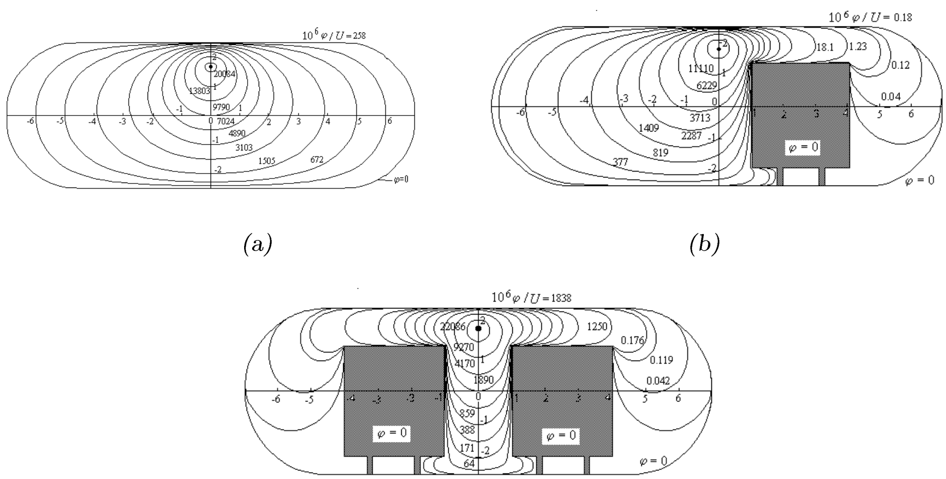
3.3 Examples for mine pit

The aim of these examples is to determine the electromagnetic field distribution in a mine pit, when a wagon is inside or when it is vacant. For



(a) (b)

Fig. 10. Mathematical model of bridge when a train is in it (a) and when two trains (b) are in it.



(a) (b)

(c)

Fig. 11. Equipotential curves in the vacant tunnel (a), in the tunnel when a train is in it (b) and in the tunnel when two trains are in it (c).

these purposes, a mathematical model of the mine pit with built-in coaxial line with axial slit has been derived. There, the mine pit cross section is considered to be rectangular and the roof is approximated by means of half-circle. The mine pit walls, as well as the earth surface are assumed to be perfectly conductive. It is adopted that the wagon cross section is rectangular, considering wheels and gaps existing under the wagon. The user sets positions of the coaxial line with axial slit and its angular opening. The slit coaxial line position is determined by its axis coordinates, v_x and v_y

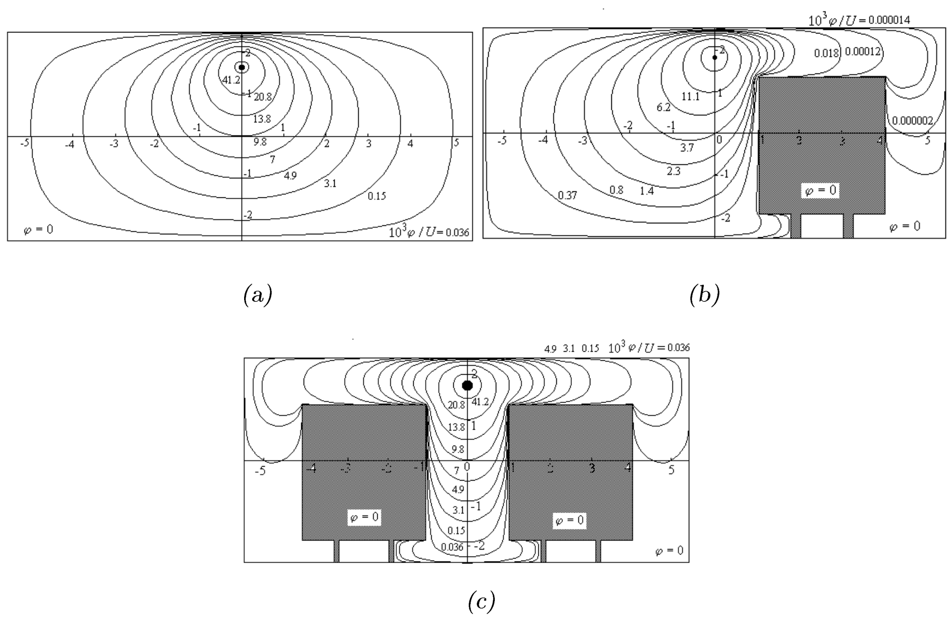


Fig. 12. Equipotential curves in the vacant bridge (a), in the bridge when a train is in it (b) and in the bridge when two trains are in it (c).

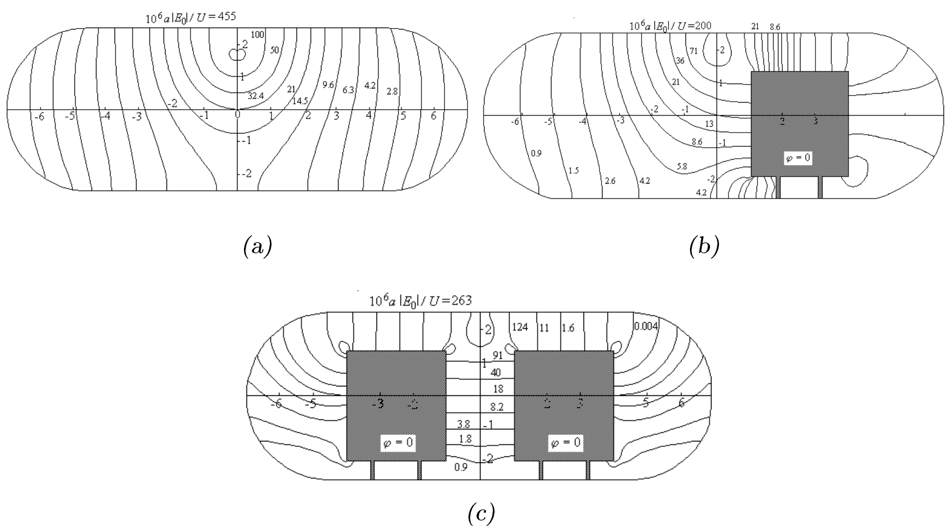
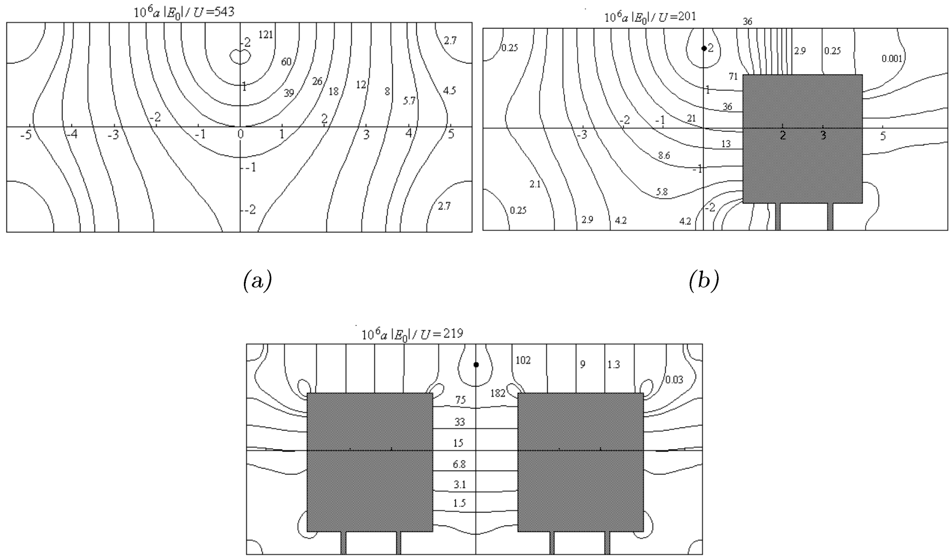


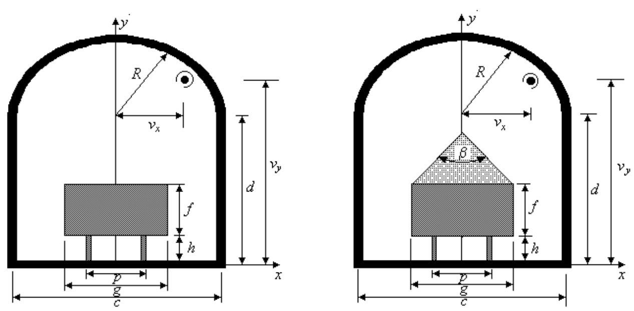
Fig. 13. Equienergetic curves in the vacant tunnel (a), in the tunnel when a train is in it (b) and in the tunnel when two trains are in it (c).



(a) (b)

(c)

Fig. 14. Equienergetic curves in the vacant bridge (a), in the bridge when a train is in it (b) and in the bridge when two trains are in it (c).



(a) (b)

Fig. 15. Mathematical model of mine pit when empty wagon (a) and when loaded wagon (b) is inside.

(Fig. 15). The slit position is determined by the angle θ_x (Fig. 16). Radius of the interior conductor of slit coaxial line is a, of shield is b and the angular width of the shield slit is 2α. The considered mine pit has dimensions given in Table 5.

These numerical results refer to the coaxial line with axial slit having ratio of shield and interior conductor radii $b/a = \mathrm{e}$ and angular width of slit

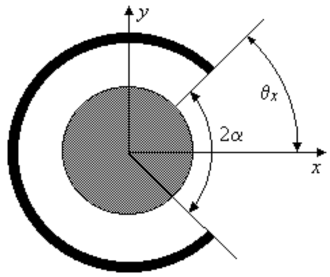


Fig. 16. The slit position of the coaxial line.

Table 5. Dimensions of mine pit (Fig. 15).

$b/a = \mathrm{e}$	$c/a = 300$	$\alpha = 50^0$	$g/a = 1200$	$\beta = 70^0$
$p/a = 800$	$d/a = 2500$	$f/a = 1000$	$R/a = 1500$	$h/a = 400$

$2\alpha = 100^0$. It is investigated two positions of the coaxial line with axial slit and two positions of its shield slit. Positions of slit coaxial line and its shield slit are given in Table 6.

Table 6. Positions of slit coaxial line and its shield slit.

			case A	case B
position	v_x/a	v_y/a	$\theta_x[^0]$	$\theta_x[^0]$
1	0	3850	220	40
2	950	3450	175	355

Equipotential and equienergetic surfaces of the coaxial line with axial slit in the mine pit, when the mine pit is vacant and when a wagon is inside, empty or loaded with ore, are shown in Figs. 17, 18, 19 and 20.

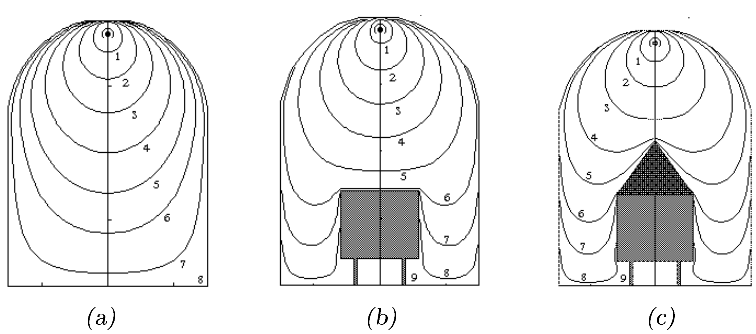
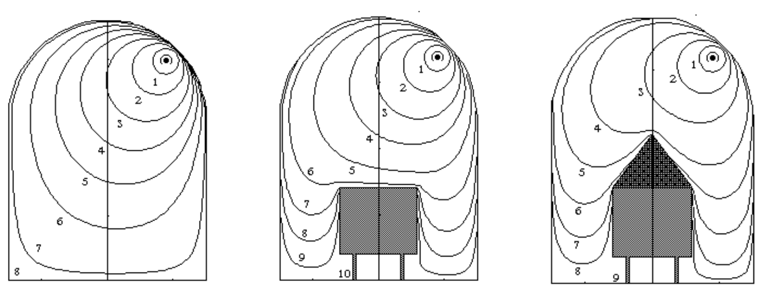


Fig. 17. Equipotential curves (Table 7) in vacant mine pit (a), when empty wagon is inside (b) and when loaded wagon is inside (c).

Table 7. The values of $10^3\varphi/U$ (position 1).

	(a)		(b)		(c)	
No	case A	case B	case A	case B	case A	case B
1	8.66609	8.66609	11.45100	11.45100	8.54624	8.54624
2	3.98839	3.98839	4.64709	4.64709	3.72107	3.72107
3	2.00535	2.00535	2.16762	2.16762	1.42155	1.42155
4	0.99242	0.99242	1.05014	1.05014	0.33986	0.33986
5	0.49920	0.49919	0.35306	0.35306	0.07296	0.07028
6	0.22728	0.22728	0.04632	0.04534	0.00956	0.00921
7	0.05097	0.05097	0.00554	0.00542	0.00161	0.00155
8	0	0	0.00054	0.00054	0.00012	0.00012
9			0	0	0	0

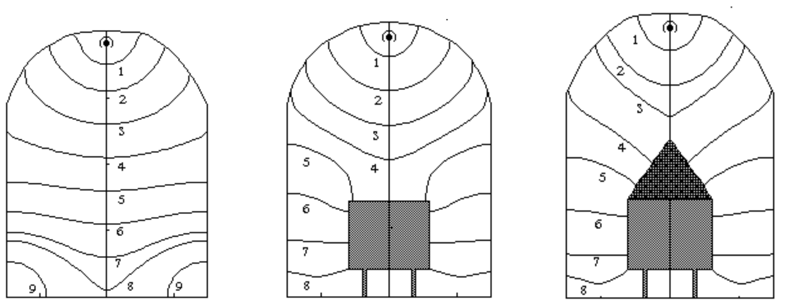


(a) (b) (c)

Fig. 18. Equipotential curves (Table 8) in vacant mine pit (a), when empty wagon is inside (b) and when loaded wagon is inside (c).

Table 8. The values of $10^3\varphi/U$ (position 2).

	(a)		(b)		(c)	
No	case A	case B	case A	case B	case A	case B
1	12.10730	8.43313	12.06390	8.40218	11.94250	8.31579
2	5.57160	3.95013	5.47611	3.88210	5.20503	3.68913
3	2.83431	2.01562	2.65901	1.89071	2.07245	1.47317
4	1.56012	1.11052	1.38611	0.98655	0.41356	0.29418
5	0.83404	0.59387	0.49315	0.35117	0.08049	0.05732
6	0.33913	0.24151	0.11374	0.08098	0.01228	0.00875
7	0.04149	0.02956	0.02174	0.01547	0.00209	0.00149
8	0	0	0.00524	0.00373	0.00046	0.00033
9			0.00101	0.00072	0	0
10			0	0		

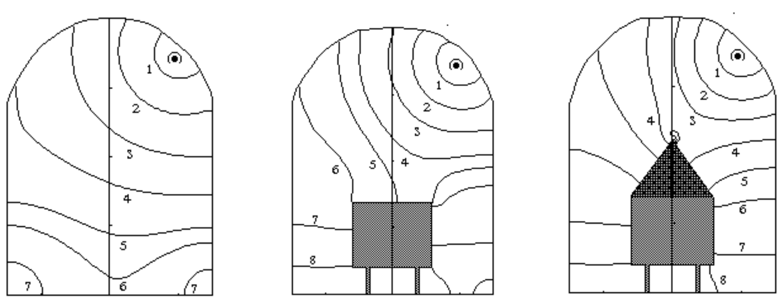


(a) (b) (c)

Fig. 19. Equienergetic curves (Table 9) in vacant mine pit (a), when empty wagon is inside (b) and when loaded wagon is inside (c).

Table 9. The value of $10^6 a|E|/U$ (position 1).

	(a)		(b)		(c)	
No	case A	case B	case A	case B	case A	case B
1	21.97250	21.97250	22.04310	22.04310	22.28060	22.28060
2	6.28768	6.28768	5.15236	5.15236	5.54610	5.54610
3	2.48798	2.48798	2.31368	2.31368	3.34242	3.34242
4	1.26858	1.26858	1.41684	1.41684	1.21153	1.17230
5	0.72333	0.72333	0.94645	0.93197	0.45200	0.43599
6	0.44515	0.44514	0.29345	0.28754	0.06777	0.06529
7	0.30539	0.30538	0.04036	0.03956	0.00840	0.00809
8	0.25436	0.25436	0.00773	0.00758	0.00256	0.00246
9	0.14963	0.14963				



(a) (b) (c)

Fig. 20. Equienergetic curves (Table 10) in vacant mine pit (a), when empty wagon is inside (b) and when loaded wagon is inside (c).

Table 10. The value of $10^6 a|E|/U$ (position 2).

	(a)		(b)		(c)	
No	case A	case B	case A	case B	case A	case B
1	35.53000	23.50620	35.65350	23.5949	35.99530	23.84080
2	6.86530	4.84024	10.14220	7.09746	10.60300	7.42557
3	2.38052	1.69174	4.74910	3.36243	5.31387	3.76478
4	1.06550	0.75852	2.46841	1.75477	2.67013	1.89907
5	0.54933	0.39123	1.69997	1.21043	1.05846	0.75408
6	0.38728	0.27592	0.94843	0.67517	0.31335	0.22311
7	0.17395	0.12390	0.07698	0.05480	0.02155	0.01535
8			0.00979	0.00697	0.00275	0.00196

4. Conclusion

The electromagnetic field in a tunnel, on a bridge and in a mine pit is determined by means of the equivalent electrodes method, when the slit coaxial lines are used for realizing a radio link and a progressive TEM wave is excited on them. In order to model the tunnel, bridge, or mine pit the plan-parallel cylindrical cavity with quite arbitrary, but known cross section is considered. The cavity walls, as well as the earth surface and train are assumed to be perfectly conductive. The influence of the train and of the walls on the field distribution is also investigated. The obtained results are very exact and converge very quickly with the increasing of the number of equivalent electrodes. The numerous results for equipotential and eqienergetic curves are presented. So it is possible to plane reliable radio link.

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