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ON THE CALCULATION OF THE VERTICAL SOIL PRESSURE ON RIGID PIPES INSTALLED IN EMBANKMENT CONDITIONS

BY

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Abstract. For the rigid pipes buried in the ground, the main exterior force is caused by the vertical pressure of the fill material and also may be caused by the traffic.

The calculation relationship of the vertical pressure of the earth on a buried rigid pipe is based on the Marston’s theory of loads. This pressure depends on a number of parameters relating to the pipe and the surrounding ground. For the pipe the parameters which count are: the outer diameter, its rigid or flexible classification, and the type of installation (in the trench, in the tunnel, in the embankment conditions). At the pipes installed in the embankment conditions, the projection rate, p, is defined according to the pipe installations position, in positive or negative projection.

The fill material parameters are more numerous and more difficult to evaluate (the specific weight γ, the product K_μ between the Rankine constant and the internal friction coefficient, the settlement ratio r_{sd}, the ratio H/B_c between the depth of burial and the diameter of the pipe). In the paper are given directions, calculation

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relations, tables with values and graphs useful for the evaluation of these parameters, as well as the load coefficient, C_c, which is a term of the vertical pressure equation of the fill material from embankment.

Parametric numerical studies, presented in the paper, aim for highlighting the influence of the above mentioned parameters, on the vertical pressure amount of the fill earth from the embankment per linear meter of the buried pipe. The tables with values, variation graphs, observations and resulting conclusions can be useful in the design of the rigid pipes buried in the embankment conditions.

Keywords: rigid buried pipe; embankment condition; soil vertical pressure; Marston-Spangler load theory; load coefficient; parametric studies.

1. Introduction

The buried pipes represent the main elements of some underground networks, being vital for actual human communities, namely: main water supply, sewage networks, heat distribution networks, Gas networks, networks for transporting oil and chemical products etc.

Applying the concept of flexibility (or stiffness) and constituent materials for pipes, allow them to be classified into two broad categories (Moser, 2001; Rajkumar & Ilamparuthi, 2008; Saadeldin *et al*., 2015):

- rigid pipes – are considered to be made of concrete, asbestos, ceramic, gray cast iron etc.; they are more rigid than the surrounding soil and will therefore bear almost all of the weight of the earth prism or load applied to the surface of the ground;

- flexible pipes - are considered to be those made of steel, ductile cast iron, plastics, reinforced composites etc.; in this case the soil is more rigid than the pipe and a significant part of the load will be supported by it.

In some particular situations, rigid pipes can gain some flexibility (for example, at large diameters), just like flexible pipes such as PVC, PEHD, aluminum etc., at small diameters become stiffer. In literature these cases are classified as semi-rigid or semi-flexible pipes (Moore, 2001; Campino de Carvalho; Liu *et al*., 2014).

Knowing and accurately evaluating the actions, which significantly influence the mechanical behavior of the buried pipes, is essential for the design process.

The external loads, to which the pipes buried in the soil are subjected, depend on the rigidity properties of both the pipe and the surrounding soil, results that the problem of soil-structure interaction is an undetermined static problem. Thus, the soil pressure on the pipeline produces displacements which, in turn, influence the pressure of the soil (Moser, 2001; Lester, 2008; Napolitano & Parlato, 2016).

Rigid pipes are mainly affected by vertical pressure caused by ground and traffic, and in this case, horizontal reactive pressure is negligible. In flexible pipes, the vertical load causes a vertical pipe displacement, which has as a result a relative horizontal pressure of the supporting soil on the lateral sides of the pipe.

Differences in mechanical behavior occur between rigid and flexible pipes and as a result of a type of installation or construction condition (Manual on Sewerage and Sewage Treatment, 1980; IS:7563-1986; Pumnia & Jain, 1998): trench conditions (in narrow trenches/ditches); embankment or projecting conduit condition; tunnel condition.

This paper analyzes aspects regarding the determination of the vertical pressure of the fill material on rigid pipes installed in embankment or projecting conduit condition, the other two cases being treated in a recent work (Vrabie *et al.*, 2017).

2. Marston-Spangler Theory for Calculating the Earth's Pressure on Rigid Pipes Installed in Embankment Condition

2.1. Parameters Definition

From Longman Dictionary of Contemporary English – an *embankment* is “a wide wall of earth or stones, built to stop water from flooding an area, or to support a road or railway”. According to Cambridge Dictionary the embankment is “an artificial slope made of earth and/or stones” and can be “a river/road/railway embankment”.

In frequent practical situations, pipeline networks are obliged to subtract communication routes so that "it is necessary to treat the problem of pipes buried in embankments" (Moser, 2001).

The type of pipe installation in embankment, where the top of the conduit is located above the natural ground, was defined by Marston as *a positive projecting conduit*. In accordance with IS:7563-1986, “This condition applies to a conduit installed in shallow bedding with its top projecting above the surface of natural ground and then covered with an embankment” (Fig. 1).

The projection ratio, *p*, indicates the relative position of the pipe in relation to the natural ground. Thus, when the pipe is installed in a narrow, superficial trench, and the top of the pipe coincides with the natural ground level, the projection ratio is null ($p = 0$). The higher top of the pipe is above the natural ground level, the higher the projection ratio is growing, so $p > 0$ ($p = 1$ if the pipe is placed directly on the surface of the natural ground and then the material fill is deposited in the embankment).

It should also be noted that, in order to increase the height of the earth cover layer, respectively the installation depth, the type of installation as a *negative projecting conduit* is also used. From source IS:7563-1986 we can see that "This condition applies to a conduit installed in a relatively narrow and shallow trench with its top at an elevation below the natural ground surface and having a superimposed fill above the top of trench".

For the buried pipe in the embankment it is possible to express the distance from the top of the pipe to the surface of the natural ground through the pB_c product (Fig. 1).

Depending of the fill settlement on the sides of the pipe is defined the settlement ratio parameter, r_{sd}, and two situations are possible:

a) the ground on the sides of the pipe settles more than the top of the pipe, in which case the shear forces are descending and cause a larger load on the buried pipe. This case, illustrated in Fig. 1 *a*, is characterized by a positive r_{sd} settlement ratio, and was called by Marston - the projection condition.

b) the upper part of the pipe settles more than the ground on the sides of the pipe, in which case the shear forces are upward and lead to a lower load on the pipe. The case, illustrated in Fig. 1 *b*, is characterized by a negative settlement ratio and is called ditch condition (pit/trench condition or ditch condition).

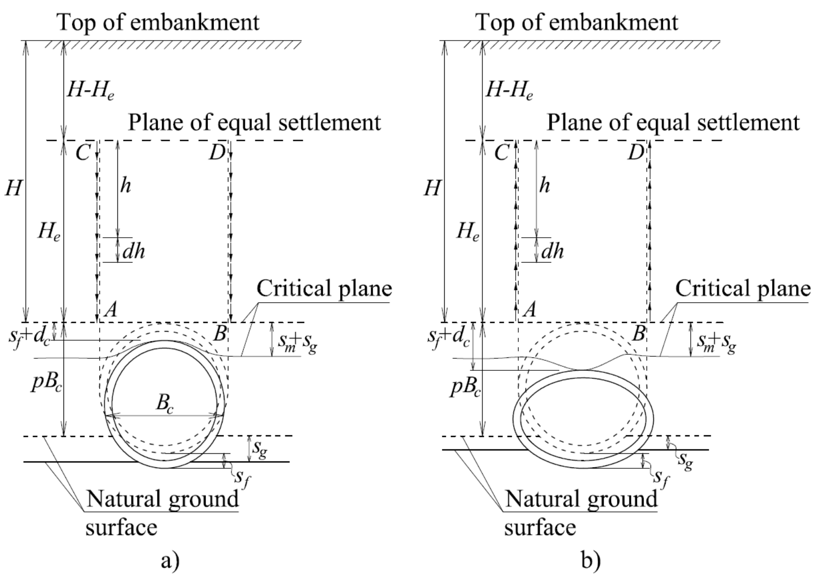

Fig. 1 – Two cases of positive projecting conduits: *a* – the projection condition; *b* – ditch condition (adaptation from source: Moser, 2001).

Regarding the *settlement ratio*, r_{sd}, it is mathematically defined as the relationship

$$r_{sd} = \frac{\left(S_m + S_g\right) - \left(S_f + d_c\right)}{S_m}, \tag{1}$$

in which the meanings of the parameters are in accordance with Fig. 1: S_m – deformation (compaction) in the ground adjacent to the pipe; S_g – compaction of the surface of the natural ground on the lateral sides of the pipe; S_f – settlement of foundation underneath pipe; d_c – deflection of the top of pipe.

The plan at the top of the pipe, called the critical plane, is compressed with the $S_m + S_g$, and the upper part of the pipe is compressed to $S_f + d_c$. If the settlement of the critical plane becomes equal to compressing the upper part of the pipe, therefore, the equality equation is

$$S_m + S_g = S_f + d_c. \tag{2}$$

Then the settlement ratio is null ($r_{sd} = 0$).

The settlement ratio is empirically determined by direct observation and is difficult to determine this through the analytical methods. Some values used in practice are presented in (Pumnia *et al.*, 2005) or Table 1, according to Moser, (2001).

Table 1
Design Value of Settlement Ratio

No.	Conditions	Settlement ratio
1	Rigid culvert on foundation of rock or unyielding soil	+1,0
2	Rigid culvert on foundation of ordinary soil	+0,5 to +0,8
3	Rigid culvert on foundation of material that yelds with respect to adjacent natural ground	0 to +0,5
4	Flexible culvert with poorly compacted side fills	–0,4 to 0
5	Flexible culvert with well-compacted side fills	–0,2 to +0,8

Another parameter required in the analysis, highlighted in Fig. 1 is a horizontal plane at which shear forces are null, called *plane of equal settlement*. The exterior soil prism (located above this plane) and the inner prism settles even.

If the plane of equal settlement is real, namely, it is located inside the embankment; it is an *incomplete projection/ditch condition* (an incomplete condition of prominence or trench).

If the plane of equal settlement is imaginary, namely, the shear force extends to the top of the embankment; it is about the *complete projection/ditch condition* (a complete condition of prominence or trench).

2.2. Calculation of Ground Pressure on the Rigid Pipe Buried in the Embankment

2.2.1. *Positive Projection Condition*

The linear loading on the rigid pipe installed in the backfill in the positive projection condition is deduced from Marston's relationship

$$W_c = C_c \gamma B_c^2, \tag{3}$$

where: C_c is a non-dimensional loading coefficient, γ is the specific weigth of the fill material from embankment, and B_c is the outer diameter of the pipe.

Loading coefficient, C_c, for the complete condition is written

$$C_c = \frac{\mathrm{e}^{\pm 2K\mu(H/B_c)} - 1}{\pm 2K\mu}, \tag{4}$$

and for the incomplete condition has the form:

$$C_c = \frac{\mathrm{e}^{\pm 2K\mu(H_e/B_c)} - 1}{\pm 2K\mu} + \left(\frac{H}{B_c} - \frac{H_e}{B_c}\right)\mathrm{e}^{\pm 2K\mu(H_e/B_c)}. \tag{5}$$

In the expressions (4) and respectively (5), the (+) sign is for the projection condition and the (–) sign for the ditch condition. It should also be noted that if the height of the plane of equal settlement, H_e, becomes equal to the height of the pipe cover layer, H, then the expression (5) for the incomplete condition is reduced to the expression (4) for the complete condition.

For the complete condition, the load coefficient, C_c, is a function of the product $K\mu$ (between the Rankine constant, K, and the friction coefficient of the fill, μ), as well as the H/B_c ratio (between the cover layer height and the outer diameter of the pipe). The coefficient of friction and Rankine constant (ratio of lateral to vertical earth pressure) is expressed according to the angle of internal friction of the fill material, φ:

$$\mu = \tan\varphi; \;\; K = \tan^2\left(45 - \frac{\varphi}{2}\right). \tag{6}$$

Some typical values of the parameters γ, K and μ have been experimentally determined by Martson and are given, for example, in Table 2.1, p. 15 from Moser, (2001), or such as has been rearranged and adjusted according to SI system (Vrabie *et al*., 2017) in Table 2.

Table 2
Approximate Values for the PARAMETERS γ, K and μ

Soil type	γ, [kN/m^3]	K	μ	max $K\mu$	Indicative/ description
Granular materials without cohesion	–	–	–	0.1924	A – granular materials
Dry sand	15.9	0.33	0.50	0.165	B – sand and gravel
Wet sand	19.1				
Partially compacted damp topsoil	14.3				
Saturated topsoil	17.5	0.37	0.40	0.148	C – saturated topsoil
Partially compacted damp clay	15.9	0.33	0.40	0.132	D – ordinary clay
Saturated clay	19.1	0.37	0.30	0.111	E – saturated clay

The values recommended in (Moser, 2001) for the product $K\mu$ of the fill material from embankment are 0.19 in the condition of prominence and 0.13 in the trench condition.

For the incomplete condition, in addition to the above mentioned parameters, the H_e/B_c ratio between the height of the plane of equal settlement and the diameter of the pipe also is added. As the H_e parameter represents a fraction of the prism height of the pipe coverage, H, it can be set in accordance with the parameters defined in paragraph 2.1 (projection ratio, p, and settlement ratio r_{sd}). Thus, these parameters are incorporated into the Marston load equation by the load coefficient C_c, which is also the function of the pr_{sd} product:

$$C_c = f\left(K\mu,\ H/B_c,\ pr_{sd}\right). \tag{7}$$

Since the expression (5) of the C_c coefficient for the incomplete condition is rather complicated, it has been transformed into more simple individual forms to facilitate graphical representation. Thus, according to Spangler & Handy, (1982), Table 3 shows the simplified expressions of the C_c coefficient, based on the H/B_c ratio and the various values of the pr_{sd} product ecountered in practice. The table was completed by the authors of the present paper, at the end, with the two complete (rising and trench) conditions, customized for $K\mu = 0.19$, respectively $K\mu = 0.13$.

Table 3

Particular Expressions of the C_c Coefficient Function of the H/B_c Ratio

Incomplete projection condition $K\mu = 0.19$		Incomplete ditch condition $K\mu = 0.13$	
$r_{sd}\,p$	Equation C_c =	$r_{sd}\,p$	Equation C_c =
+ 0.1	$1.23\ H/B_c - 0.02$	– 0.1	$0.82\ H/B_c + 0.05$
+ 0.3	$1.39\ H/B_c - 0.05$	– 0.3	$0.69\ H/B_c + 0.11$
+ 0.5	$1.50\ H/B_c - 0.07$	– 0.5	$0.61\ H/B_c + 0.20$
+ 0.7	$1.59\ H/B_c - 0.09$	– 0.7	$0.55\ H/B_c + 0.25$
+ 1.0	$1.69\ H/B_c - 0.12$	–1.0	$0.47\ H/B_c + 0.40$
+ 2.0	$1.93\ H/B_c - 0.17$		
Complete projection condition (CPC)		Complete ditch condition (CDC)	
$C_c = \dfrac{e^{2K\mu(H/B_c)} - 1}{2K\mu} = \dfrac{e^{0.38(H/B_c)} - 1}{0.38}$		$C_c = \dfrac{e^{-2K\mu(H/B_c)} - 1}{-2K\mu} = \dfrac{e^{-0.26(H/B_c)} - 1}{-0.26}$	

Table 4 shows the numerical values of the coefficient C_c, calculated on the basis of the expressions from Table 3, for different H/B_c and pr_{sd} values, which are possible in practice, and the graphical representation is given in Fig. 2.

Table 4

Numerical Values of the C_c coefficient

$r_{sd}\,p$ \ H/B_c	0	1	2	3	4	5	6	7	8	9	10
CDC	0.00	0.88	1.56	2.08	2.49	2.80	3.04	3.22	3.37	3.48	3.56
–1.0	0.40	0.87	1.34	1.81	2.28	2.75	3.22	3.69	4.16	4.63	5.10
–0.7	0.25	0.80	1.35	1.90	2.45	3.00	3.55	4.10	4.65	5.20	5.75
–0.5	0.20	0.81	1.42	2.03	2.64	3.25	3.86	4.47	5.08	5.69	6.30
–0.3	0.11	0.80	1.49	2.18	2.87	3.56	4.25	4.94	5.63	6.32	7.01
–0.1	0.05	0.87	1.69	2.51	3.33	4.15	4.97	5.79	6.61	7.43	8.25
0.00	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
+0.1	0.02	1.21	2.44	3.67	4.90	6.13	7.36	8.59	9.82	11.05	12.28
+0.3	0.05	1.34	2.73	4.12	5.51	6.90	8.29	9.68	11.07	12.46	13.85
+0.5	0.07	1.43	2.93	4.43	5.93	7.43	8.93	10.43	11.93	13.43	14.93
+0.7	0.09	1.50	3.09	4.68	6.27	7.86	9.45	11.04	12.63	14.22	15.81
+1.0	0.12	1.57	3.26	4.95	6.64	8.33	10.02	11.71	13.40	15.09	16.78
+2.0	0.17	1.76	3.69	5.62	7.55	9.48	11.41	13.34	15.27	17.20	19.13
CPC	0.00	1.22	3.00	5.60	9.40	14.96	23.10	34.99	52.38	77.81	115.00

The theoretical analysis and graphic representation indicate that when the product $pr_{sd} = 0$ results $C_c = H/B_c$, which leads to a linear load on pipe:

$$W_c = C_c \gamma B_c^2 = \frac{H}{B_c} \gamma B_c^2 = \gamma H B_c, \quad (8)$$

results that, the load is the earth prism weight situated above the pipe. This is possible in two situations:

1) If the projection ratio $p = 0$, namely, the upper part of the buried pipe coincides with the natural ground level;
2) If the settlement ratio $r_{sd} = 0$, namely, the settlement of the critical plane becomes equal to the deformation of the upper part of the pipe (regardless of its position in the embankment).

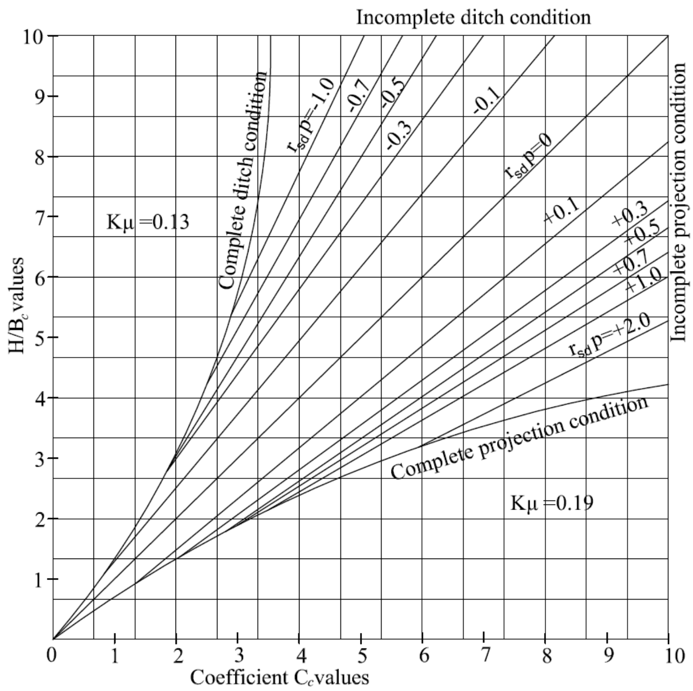

Fig. 2 – Diagram of the C_c coefficient for buried pipes in positive projection (adaptation by source: Moser, 2001).

2.2.2. *Negative Projection Condition*

The loading on a linear meter of a rigid pipe installed in the embankment in the negative projection condition is deduced from the relation (Campino de Carvalho):

$$W_c = C_n \gamma B_d^2, \tag{9}$$

in which, the loading coefficient, C_n, for the complete condition is written

$$C_n = \frac{1 - \mathrm{e}^{-2K\mu(H/B_d)}}{2K\mu}, \tag{10}$$

or, for the incomplete condition

$$C_n = \frac{1 - \mathrm{e}^{-2K\mu(H_e/B_d)}}{2K\mu} + \left(\frac{H}{B_d} - \frac{H_e}{B_d}\right)\mathrm{e}^{-2K\mu(H_e/B_d)}. \tag{11}$$

Eq. (9) is similar in shape to Eq. (3), specifying that the diameter B_c of the pipe in Eq. (3) is now replaced by the width of the trenches, B_d (Fig. 3).

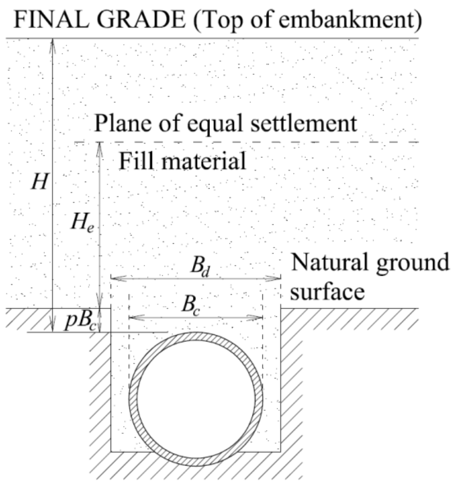

Fig. 3 – Pipe in negative projection installed in the embankment.

To be highlighted that, for the complete condition, the C_n load coefficient becomes identical to the one from the installation in the ditch, C_d (Moser, 2001).

3. Numerical Parametric Studies

In order to highlight the influence of the parameters H/B_c, γ and $K\mu$, the vertical soil pressure is calculated on a concrete rigid pipe, buried in embankment condition as a positive projecting conduit. Taking into account the parameters γ and $K\mu$, there are two distinct cases:

Case 1: Fill material is partially compacted damp clay (γ = 15,9 kN/m^3; max $K\mu$ = 0,13) – complete ditch condition (CDC);

Case 2: Fill material is granular material without cohesion (γ = 12 kN/m^3; max $K\mu$ = 0.19) – complete projection condition (CPC).

Five different values for the pipe diameter (0.5, 1.0, 1.5, 2.0, 2.5) m were considered, but the *H* values of the fill material from embankment were chosen such that the H/B_c ratio should be kept constant (1; 2; 3; 4; 5). In this way, the C_c values of the load coefficient calculated in Table 4 could be used. A systematization of the input data used and the results obtained for the prism loading, P_p, respectively for the vertical pressure in the embankment per linear meter of pipe, W_c, (in kN/m), is shown in Table 5.

Table 5

Calculation of the Vertical Pressure from the Embankment per Linear Meter of Pipe

B_c, [m]	H, [m]	P_p, [kN/m]		W_c, [kN/m]	
		Case 1	Case 2	Case 1	Case 2
0.5	0.5	3.975	3	3.498	3.66
	1.0	7.95	6	6.201	9
	1.5	11.925	9	8.268	16.8
	2.0	15.9	12	9.898	26.2
	2.5	19.875	15	11.13	44.88
1.0	1.0	15.9	12	13.992	14.64
	2.0	31.8	24	24.804	36
	3.0	47.7	36	33.072	67.2
	4.0	63.6	48	39.591	112.8
	5.0	79.5	60	44.52	179.52
1.5	1.5	33.375	27	31.482	32.94
	3.0	71.55	54	55.809	81.0
	4.5	107.325	81	74.412	151.2
	6.0	143.1	108	89.080	253.8
	7.5	178.875	135	100.17	403.92
2.0	2.0	63.6	48	55.97	58.56
	4.0	127.2	96	99.22	144
	6.0	190.8	144	132.29	268.8
	8.0	254.4	192	158.36	451.2
	10.0	318	240	178.08	718.08
2.5	2.5	99.37	75	87.45	91.5
	5.0	198.75	150	155.02	225
	7.5	298.12	225	206.7	420
	10.0	397.5	300	247.44	705
	12.5	496.87	375	278.25	1,122

The graphical representation of the vertical pressure variation W_c, as a function of the H/B_c ratio, for the pipe with B_c=0.5m and B_c=2.5m is illustrated in the graphs in Fig. 4 and Fig. 5.

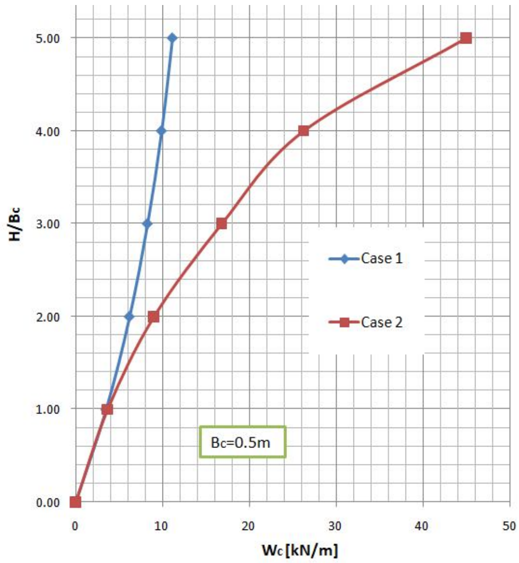

Fig. 4 – Variation of vertical pressure for pipe with B_c = 0.5 m.

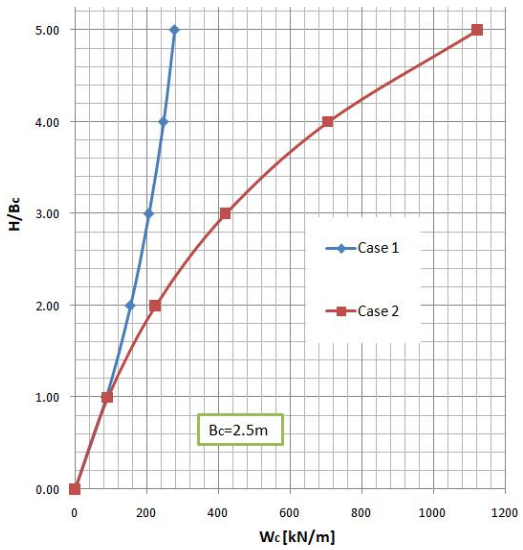

Fig. 5 – Variation of vertical pressure for pipe with B_c = 2.5 m.

A representation of the variation of W_c in relation to the height of the soil cover layer H for all five diameters chosen for the pipe is illustrated in Fig. 6 (for the embankment made of the fill material from Case 2).

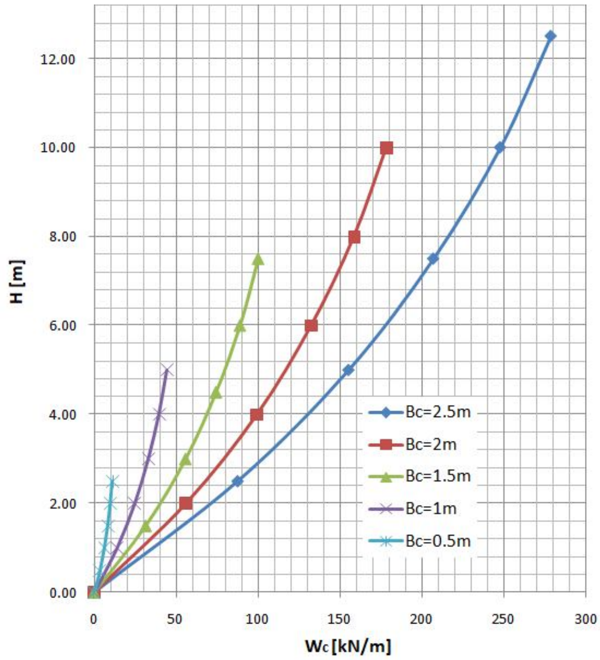

Fig. 6 – Vertical pressure variation depending on the installation depth of the pipe in embankment.

4. Conclusions and Observations

The calculation of the vertical pressure of the fill material on the rigid pipes installed in the embankment, using the Marston-Spangler theory, follows an algorithm which is similar to the installation into the trench. The relation of earth pressure calculation to the pipe does not differ in shape, but the parameters involved are more numerous and more difficult to evaluate. In fact, these parameters refer to the pipe, the fill material and the interaction between the pipe and the fill material from embankment.

The essential parameter of the pipe is its outer diameter, B_c (at installation in positive projection), or the width of the narrow superficial trench, B_d (when installing the pipe in negative projection). The concept of flexibility (or rigidity), as well as how to install the pipe embankment (through the projection ratio, *p*) are other parameters to be taken into account in the calculating the vertical pressure.

The properties of the fill material from embankment that influences its vertical pressure are the specific weight, γ, the product $K\mu$, between the Rankine constant and the internal friction coefficient, the r_{sd} settlement ratio and the height or thickness H of the fill material layer situated above the pipe. The H/B_c interaction parameter enters also explicitly in the calculation relation of the C_c load coefficient.

The calculated values and the graphs of variation plotted for C_c, as well as the numerical parametrical studies, indicates that for the fill materials with the negative settlement ratio (ditch condition), the vertical pressure is less than the load from the earth prism of the corresponding pipe. In contrast to this fact, for fill materials with the positive settlement ratio (projection condition), the vertical pressure on the pipe exceeds the prism load.

The obtained results from numerical parametric studies may be used in designing process of the rigid buried pipes in embankment condition.

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DESPRE CALCULUL PRESIUNII VERTICALE A PĂMÂNTULUI ASUPRA CONDUCTELOR RIGIDE INSTALATE ÎN RAMBLEU

(Rezumat)

La conductele rigide îngropate în teren, principala acţiune exterioară este presiunea verticală a materialului de umplutură, precum şi cea cauzată de trafic.

Relaţia de calcul a presiunii verticale a pământului asupra unei conducte rigide îngropate în teren se bazează pe teoria de încărcare a lui Marston. Această presiune depinde de o serie de parametri referitori la conductă şi la terenul înconjurător. Pentru conductă contează diametrul exterior, clasificarea sa ca rigidă sau flexibilă, precum şi tipul de instalare (în tranşeu, în tunel, în rambleu). La conductele instalate în rambleu se defineşte rata proiecţiei, p, conform căruia conducta poate fi instalată în proiecţie pozitivă sau negativă.

Parametrii referitori la materialul de umplutură sunt mai numeroşi şi mai dificil de evaluat (greutatea specifică γ, produsul $K\mu$ dintre constanta Rankine şi coeficientul de frecare interioară, rata tasării r_{sd}, raportul H/B_c dintre adâncimea de îngropare şi diametrul conductei). În lucrare se dau indicaţii, relaţii de calcul, tabele cu valori şi grafice, utile pentru evaluarea acestor parametri, precum şi a coeficientului încărcării, C_c, care intră în relaţia de calcul a presiunii verticale a materialului de umplutură din rambleu.

Studiul numeric parametric, prezentat în lucrare, are menirea de a pune în evidenţă influenţa parametrilor prezentaţi mai sus, asupra mărimii presiunii verticale a materialului de umplutură din rambleu pe metru liniar de conductă îngropată. Tabelele cu valori, graficele de variaţie, observaţiile şi concluziile rezultate, pot fi utile în proiectarea curentă a conductelor rigide îngropate în rambleu.