A METHOD FOR ASSESSING EMBANKMENT SETTLEMENT DUE TO THE WIDENING OF ROAD CROSS-SECTION

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ABSTRACT

A simple analytical and sufficiently approximate method has been devised for estimating the extent of maximum embankment settlement caused by cross-section road widening. For this purpose a series of numerical calculations was carried out by means of simplified approaches using traditional methods for settlement assessment. The values of the main parameters involved in the calculations were varied, which included the extent of the widening, the embankment height, the stiffness both of the subsoil as well as of the materials forming the embankment. The comparison with calculation findings made by a finite element model proved that the settlements obtained through the simplified approaches are sufficiently well approximated. Regression analyses of the results obtained with the simplified approach were developed in order to find out relationships which directly provided the values of the maximum settlement in function of the geometry of the system and of the material properties. After this, both traditional as well as innovative engineering techniques which are used for reducing consolidation settlements and their effects on the practical functionality of the infrastructure affected by the widening, were analysed. In this way a solution was devised that appears to be the most effective one, that consists in reducing the weight load on the foundation level, through the use of light materials, such as expanded clay, for the construction of the new embankment. Moreover, an assessment was made of the induced consolidation settlements, demonstrating the efficacy of the solution regarding those cases where crushed gravel or "pozzolana" is used.

KEY WORDS

ROAD CROSS-SECTION / WIDENING / EMBANKMENT / SETTLEMENTS / SUBSOIL IMPROVEMENT TECHNIQUES

1. INTRODUCTON

Growing social and economic development is for ever confirming the need to introduce changes into the geometry of many branches of the existing road network which are no longer sufficient to meet the new traffic requirements brought about by the heavy increase in demand for communication.

One of the more current infrastructure undertakings of functional adaptation consists in the widening of cross road-sections for the inclusion of additional lanes and eventual hard shoulders for emergency use as well as service roads. This creates serious problems amongst which, in addition to the inconvenience caused to users by the road-works, is included the preservation of the shape of the road surface, so that while it is being actually used, adequate safety levels and travel comfort may continue to exist. The functionality of the new typology of infrastructure will thus largely depend on the parameters to which the evenness of the wearing course is linked, and essentially therefore to the extent of the settlements induced by the embankment widening and their development in time.

The assessment of these settlements does not however represent a problem with a simple solution, both on account of the eventual heterogeneity of the subsoil as well as for the different stiffness of the materials making up the embankments. Indeed, readily-usable calculation methods do not exist for the designers, and those that are currently available, albeit considered sufficiently acceptable on account of the wide experience on which they are based, nevertheless have the disadvantage of having to be carried out in a rather laborious fashion which requires lengthy calculation times.

This then, is the context wherein the present work is set, that sets out to provide a simple and sufficiently approximate method for assessing the extent of the maximum embankment settlements due to the widening of the road cross-section. In order to achieve this objective settlement calculations were made by approximate approaches which use traditional methods (Skempton and Bjerrum for fine-grained soils and aedometric ones for coarse-grained soils). In the analyses the values of the main geometrical and mechanical characteristics which come into play were varied, and included: the extent of the widening, the embankment height, the stiffness of the soils below ground level, the stiffness of the materials of the pre-existing embankment and those of the new one. Thus a finite element calculation model was perfected, for the solving of which appropriate software was used, to compare the settlement values thus obtained with those obtained with approximate approaches. Analyses of regression of the maximum settlements were carried out, and analytical relationships which directly gave the settlement in function of the system geometry and material properties were obtained.

Engineering techniques which could reduce the effects of the consolidation settlements were analysed. Thus a further assessment was made of the consolidation settlements induced by light material such as expanded clay, adopted for the construction of the new embankment. Finally the efficacy of such a solution was presented by comparing it with the consolidation settlements due to crushed gravel or to “pozzolana” (which is a typical pyroclastic material).

2. STUDY APPROACH

To achieve our desired goals the main methods for calculating the settlements due to the deformation of the soils and embankment materials have been examined, respectively. Thus an appropriate work methodology was adopted, and calculations made by considering different widening schemes of the cross section and various characteristics of the materials forming the subsoil and the embankment.

The study was carried out with reference to a cross section of a road with separate carriageways and with two lanes per direction. The idea was to transform this section into a wider one within which, in function of the extent of the prescribed widening, further road lanes could be included. An initial section of 15.50 m was considered and various extensions were apportioned to each side (3.75, 5.60, 7.50 and 15.00 m) with consequent overall cross-section width between 23.00 and 45.50 m. With regard to the embankments height, values of 2, 3, 5 and 10 m were forecast.

As for the subsoil, fine-grained soils (normal consolidated NC and over consolidated OC) were considered, as well as coarse-grained ones. For fine-grained soils the ground water table was assumed at the ground surface (soil unit weight γ_{sat} = 20 kN/m^3), while for coarse-grained soils the ground-water was absent (soil unit weight γ = 17 kN/m^3). Regarding stiffness, homogeneous subsoils were considered for simplicity's sake; for normal consolidated fine-grained soils, values of aedometric modulus (E_{ed}) of 5, 6 and 7.5 MPa were adopted, while for over-consolidated ones values of 10, 15 and 20 MPa. Coarse-grained soils were characterized by aedometric moduli of 20, 25, 30, 50, 60 and 75 MPa. The range of pre-selected values is representative of the conditions generally encountered for the two types of soils.

For the existing embankment and for the widening one it was decided to utilize two types of material commonly adopted in practice: an ordinary crushed gravel (density of 20 kN/m^3 after compaction) or a lighter one such as "pozzolana" (density of 16 kN/m^3 after compaction). As for stiffness, for each of the two materials, two different values of the aedometric modulus were considered: 50 and 100 MPa for the crushed gravel, and 10 and 30 MPa for the "pozzolana", respectively.

We then proceeded to assessing the settlements of the embankment surface by articulating the calculation into two phases: first, by assessing the settlements at the foundation level, due to the weight of the new embankment; and then by assessing the deformations of the materials making up the embankments. The criterion followed in calculating the foundation-level settlements was the one commonly adopted in practice, namely an estimation of the elastic stress field due to the weight of the new embankment, and then the determination of the permanent settlements by utilizing the pre-selected calculation method. For the fine-grained soils, the final settlement was calculated as the sum of the immediate one (which takes place in non-drained conditions during widening) and the consolidation one (the settlement which develops in time in drained conditions, for the gradual dissipation of the pore pressures and the corresponding increase in the effective stress); for the coarse-grained soils (endowed with high permeability) the final settlement was calculated directly, which in practice is contextually verified at load application. With regard to the deformations accumulated in the embankment (due to the weight itself), a method found in the literature was used, which will be spoken of later on; as these materials are coarse grained, all deformations occur during load application.

Furthermore, the overall subsoil-embankment system was studied by means of a finite element model, for the resolution of which an appropriate calculation code was utilized to achieve a more accurate assessment of the settlements, and to allow comparison with the results of the approximate approaches.

From the examination of the configurations of the embankments deformations, the maximum settlement was identified as the parameter representing the effects induced, which is generally verified in correspondence with the joining area between the pre-existing embankment and the new embankment. Thus regression analyses of the maximum settlements were carried out, and analytical relationships providing a direct estimation of the settlement were obtained.

Engineering techniques were then analysed to reduce the consolidation settlements and their effects on the functioning of the infrastructure.

Thus a further assessment of the consolidation settlements was made, in the case of a new embankment realised by means of light materials, such as expanded clay (density after compaction equal to 4 kN/m^3, E_{ed} = 10 MPa), in order to assess the efficacy of this solution compared with that of using crushed gravel and "pozzolana".

3. CALCULATION METHODS

In order to assess the foundation-level settlements, the increase in the stress state induced in the subsoil by the weight of the new embankment was first calculated. For this purpose the subsoil was assimilated to an ideal half-space: continuous, linearly elastic, homogeneous and isotropic. The stress distribution, induced by a trapezoidal vertical load applied on the limit surface, was assessed by utilizing the solution in a closed form proposed by Gray (Gray, 1936):

$$\sigma_z = p / \pi \bullet [\beta + x \bullet (\alpha / a) - (z/R^2{}_2) \bullet (x-b)] \quad (1)$$

$$\sigma_x = p / \pi \bullet [\beta + x \bullet (\alpha / a) + (z/R^2{}_2) \bullet (x-b) + (2z/a) \bullet \ln(R_1/R_o)] \quad (2)$$

in which for the significance of the parameters, reference is made to Figure 1.

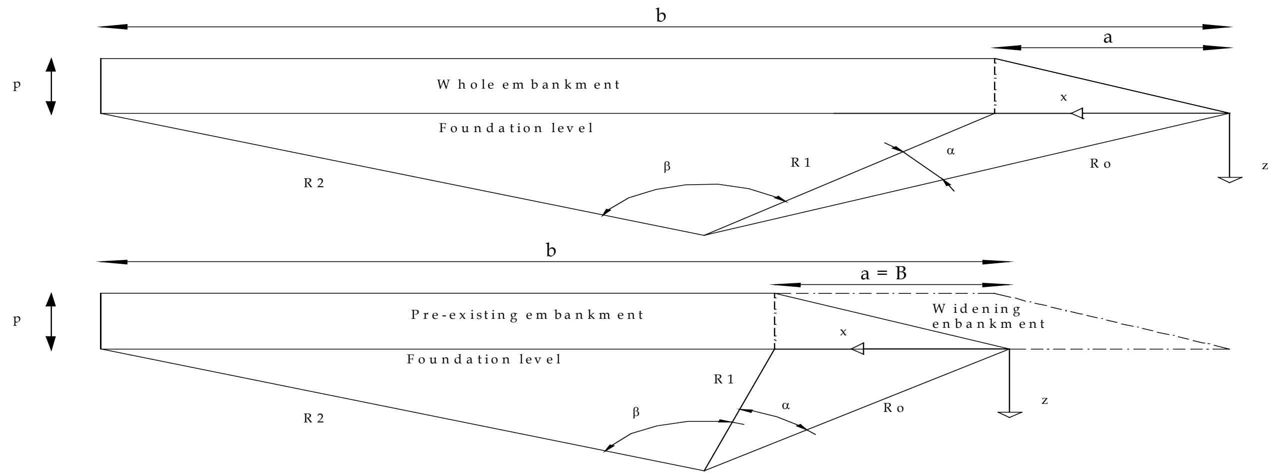

Figure 1 - Schematic section of the trapezoidal vertical load and definition of the geometrical parameters which come into Gray's method for assessing the stress induced in the subsoil.

These analytical expressions show that in the assumed hypotheses the stress values are a function only of the applied load and geometry of the problem and not of the properties of the soils. The increase in the stress state induced in the subsoil by the new embankment was calculated as the difference between the stress state caused by the overall embankment (pre-existing + new embankment) and that due to the pre-existing embankment alone. The calculation was made to a depth equal to double the width of the widening. Prior to this calculation, account had been taken of the improving effects of the weight of the pre-existing embankment on the mechanical characteristics of the soils. This was done approximately by introducing a parameter K_i, multiplicative of the modulus E_{ed} of the soil (as defined in paragraph 2). This parameter is determined as follows :

$$K_i = [(\Delta\sigma_{z(i)} + \sigma'_{z\ geost(i)}) / \sigma'_{z\ geost(i)}] \quad (3)$$

where $\Delta\sigma_{z(i)}$ is the total vertical stress increase (coinciding with the effective one) induced in the node (i) by the old embankment and $\sigma'_{z\ geost(i)}$ is the vertical effective geostatic stress existing in the same node. Clearly the values of K_i are greater than 1 and increase the aedometric moduli: $E_{ed,i} = K_i \bullet E_{ed}$.

Regarding the calculation of the settlements of fine-grained soils, the Skempton and Bjerrum method was used (Skempton and Bjerrum, 1957). This method, which is rigorous for the vertical in axis to the load, was here used approximately also for the various ground-level points. As is commonly known, the method allows assessing the final settlement w_f as sum of the immediate one w_o and the consolidation one w_c. The calculation of the immediate settlement was carried out after first subdividing the whole compressible subsoil into homogeneous layers by using the equation:

$$w_o = q \bullet B \bullet (I_1/E_{o1} + (I_2 - I_1/E_{o2}) + \dots\dots + (I_i - I_{i-1}/E_{oi}) + \dots\dots) \quad (4)$$

where q is the uniform vertical load at ground level, B is the characteristic dimension of the load, I_i is an a-dimensional coefficient dependent on the geometry of the problem (i.e. the thickness of the layer (i) and the load characteristic dimension B), E_{oi} is the elastic modulus in undrained conditions. E_{oi} values ranging between 15 and 20 MPa for the normal consolidated soils and between 25 and 30 MPa for the overconsolidated ones have been assumed. Such values, previously being utilised for assessing the settlements, were themselves multiplied by the above-mentioned parameter K_i, to take account of the improvement in the properties of the soils due to the pre-existing embankment. With regard to the consolidation settlement, this was assessed as follows:

$$w_c = \sum_i^n (\sigma_{zo,i}/E_{ed,i}) \bullet [\, A + (\sigma_{xo,i}/\sigma_{zo,i}) \bullet (1-A)] \bullet \Delta z_i \quad (5)$$

where $\sigma_{zo,i}$ e $\sigma_{xo,i}$ are the total stresses respectively in vertical and horizontal directions which are generated in the node (i) when the load is applied (that is when the new embankment is completed), $E_{ed,i}$ is the aedometric modulus in the node (i) ($E_{ed,i} = K_i \bullet E_{ed}$), Δz_i is the layer (i) thickness having its barycentre in the node (i), A is the so-called Skempton coefficient which diminishes by passing from the normally consolidated soils to over-consolidated ones (in the calculation A= 0.5 and A=0.2 are assumed respectively).

For the coarse-grained soils the aedometric method was chosen (Terzaghi and Peck, 1948), thus hypothesising for simplicity's sake that the volume elements become deformed with impeded lateral strain. The final settlement was assessed directly, given by:

$$w_{ed} = \sum_i^n (\Delta\sigma_{z,i}/E_{ed.i}) \bullet \Delta z_i \quad (6)$$

where $\Delta\sigma_{z(i)}$ is the total vertical stress increase in the node (i) due to the weight of the new embankment.

For the assessment of the settlements due only to the deformation of the materials making up the embankment, the solution proposed by Clough and Woodward was adopted for use (Clough and Woodward, 1967):

$$w\,(z) = I(z/h, h/H) \bullet \gamma \bullet (H^2/E) \quad (7)$$

where the settlement at a generic level z from the embankment base (supposed fixed, see Figure 2) is expressed in function of the so-called coefficient of influence I (in its turn function of the ratios z/h and h/H, where h is the real embankment height and H is the height of the triangle as indicated in Figure 2), of the unit weight γ, of the modulus E of the material and of H^2. For the assessment of the settlement at the top surface of the embankment equation (7) was utilized, clearly making level z coincide with embankment height h.

To verify the results of the simplified approaches, useful indications may be drawn from comparing the settlements measured in situ and/or with those obtained by using more rigorous methods; the latter appears the only way to be followed when there is no consolidated experience on the effective behaviour of works carried out by new project operations, like those of widening the existing embankments. In the present work it was therefore decided to make an assessment of the settlements also through the finite

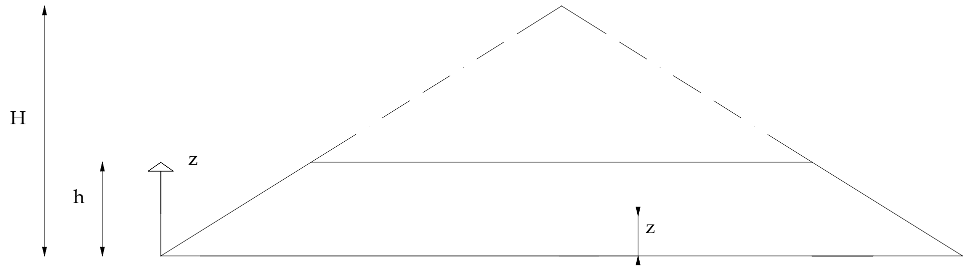

Figure 2 - Definition of the geometric parameters contained in the Clough and Woodward method for the calculation of the settlements of the embankment caused by its own weight.

element method. The geometric generation of the finite element model was achieved through an appropriate graphic interface. In an attempt to assess the optimal mesh, the relative scale factor was varied in such a way as to obtain ever smaller-sized meshes. The procedure was interrupted when a further thickening of the same did not lead to significant variations in the extent of the settlements. The final model was made up of flat triangular-type elements with 6 nodes with a 0.3 F scale factor. In the analysis the behaviour of the subsoil and material constituting the embankment was, at any rate, represented with a perfectly linear plastic elastic model. Their properties were defined through elastic modulus, Poisson coefficient, unit weight, permeability, cohesion and friction angle. The calculation was articulated into two phases: assessment of the settlements due only to the pre-existing embankment and of those caused by the overall embankment (pre-existing + widening), thus obtaining by the difference those settlements due to the new embankment only. In Figure 3 is shown a view of the complete model, with the definition of the geometry, with reference to the heaviest case (widening B equal to 15 m and embankment height H equal to 10 m, for which a depth of the compressible soil layer of 30 m is assumed). Furthermore, the configuration of the ground-level deformation and consequently that of the embankment deformation is shown.

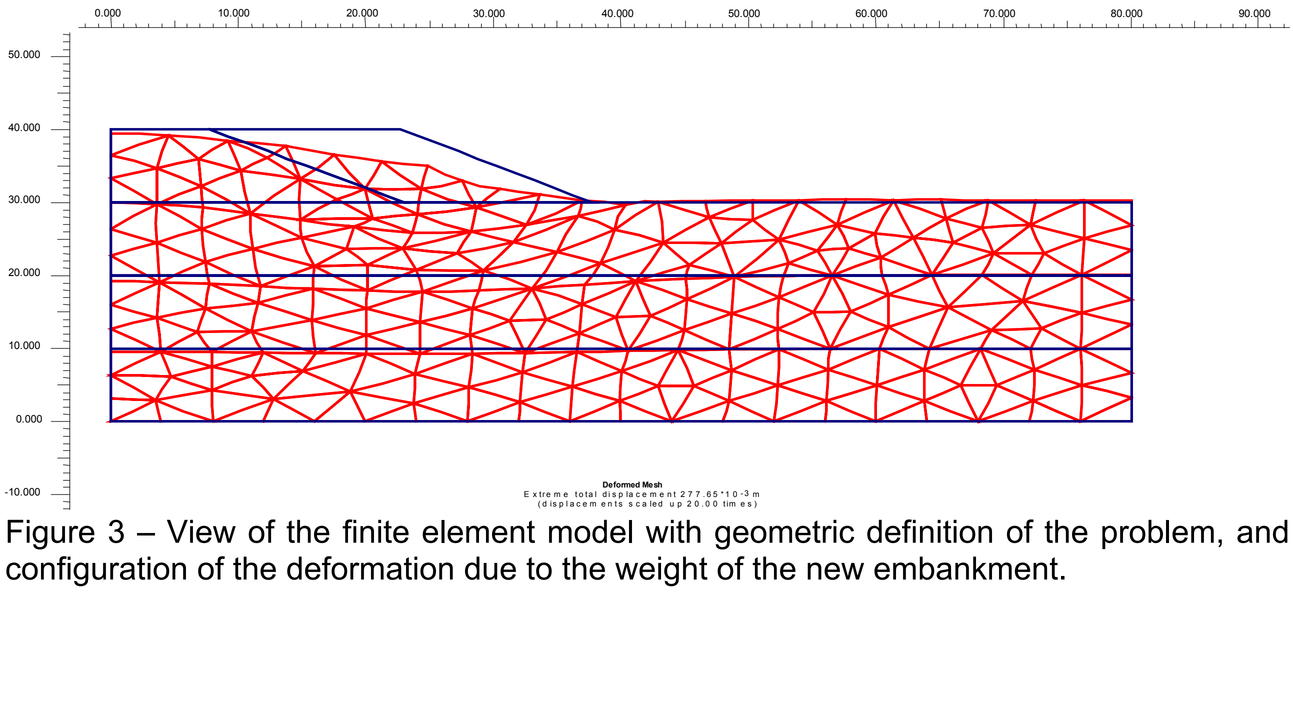

Figure 3 – View of the finite element model with geometric definition of the problem, and configuration of the deformation due to the weight of the new embankment.

It is expedient to point out that the maximum settlements of the ground level are verified in correspondence with the zone of attachment between the existing embankment and the new one. For the resolution of this model an appropriate calculation code has been utilized, namely the Plaxis (Plaxis,1998).

4. ANALYSIS OF THE RESULTS AND COMPARISON BETWEEN THE SETTLEMENTS CALCULATED WITH THE APPROXIMATE APPROACHES AND THOSE WITH THE FINITE ELEMENT METHOD

The findings of the settlement calculations are represented in apposite diagrams. For the fine-grained soils the maximum settlements of the ground level are reported for pre-determined values of the initial modulus (E_o or E_{ed}). Both the immediate (w_o) and consolidation (w_c) settlements, due to the new embankment weight (both in crushed gravel and in “pozzolana”), are reported in function of the height H and the widening B of the embankments. With reference to the embankments in crushed gravel, the trends of w_o and the corresponding consolidation settlement (w_c) are reported in Figures 4 and 5 respectively, for the normal consolidated (NC) fine-grained subsoil of poorest characteristics (E_o = 15 MPa, E_{ed} = 5 MPa).

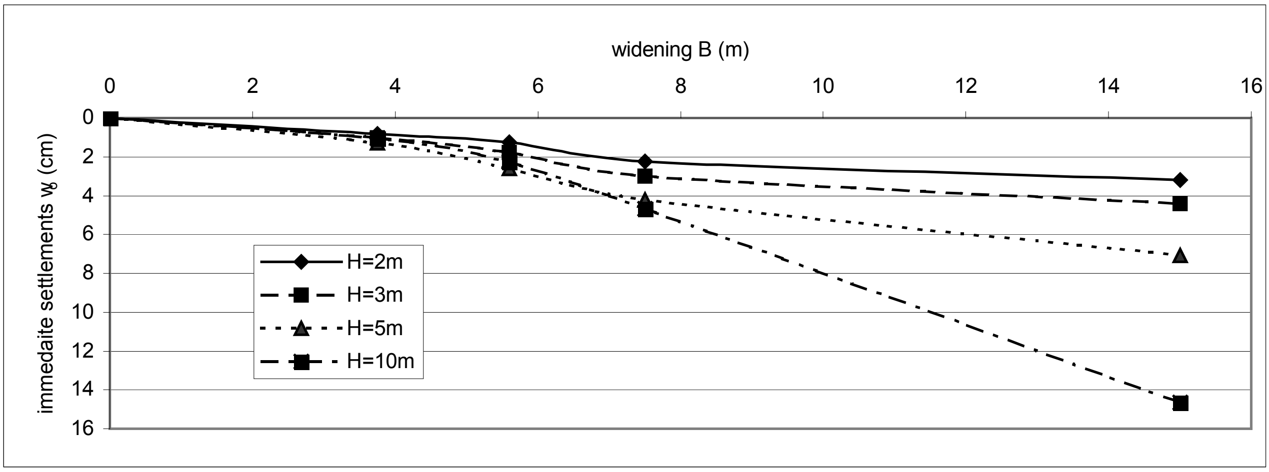

Figure 4 - Normal consolidated NC fine-grained subsoil (E_o = 15 MPa): immediate maximum settlements (w_o) of the ground level due to the weight of the crushed gravel constituting the new embankment.

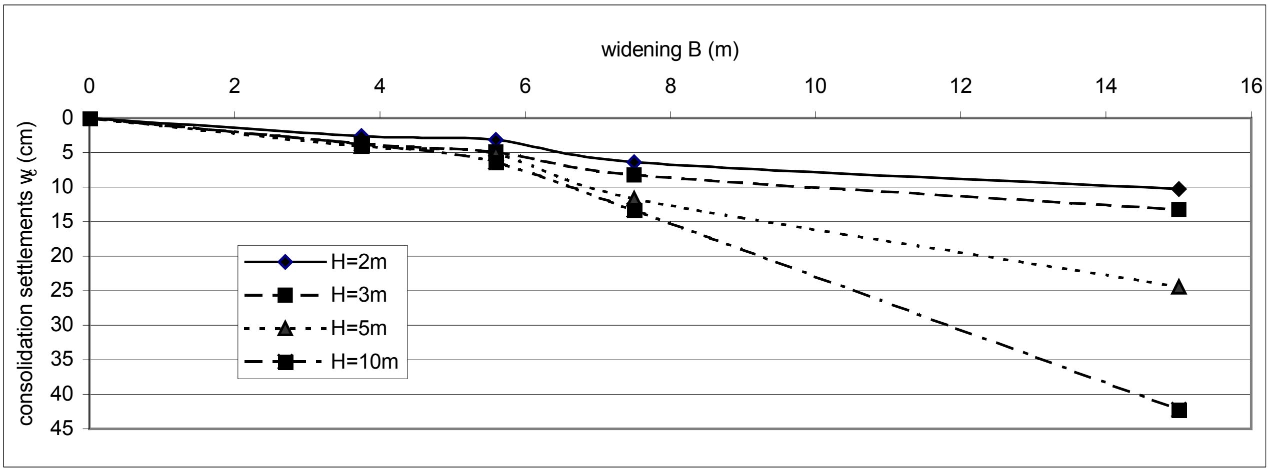

Figure 5 – Normal consolidated NC fine-grained subsoil (E_{ed} = 5 MPa): maximum consolidation settlements (w_c) of the ground level due to the weight of the crushed gravel constituting the new embankment.

These show that for the load shapes examined, the immediate and consolidation settlements increase with the extension of embankment widening B and height H. It was furthermore found that for given B and H values such settlements decrease with the value of the soil modulus. In synthesis, with reference to fine-grained soils and embankments made up of crushed gravel, the approximate approaches give immediate settlements w_o between 0.4 and 14.5 cm, and the consolidation ones w_c between 0.5 and 42.0 cm, hence final settlements w_f between 0.9 and 56.5 cm. In the cases of embankments made of "pozzolana", immediate settlements between 0.3 and 11.3 cm, and consolidation ones between 0.4 and 30.2 cm were calculated, obtaining final settlements between 0.7 and 41.5 cm. This proves that on utilizing lighter material such as pozzolana, a reduction is achieved in the settlements, which is between about 20-25% in relation to the final values.
As regards the coarse-grained subsoil, the trends of the final maximum settlements (w_f) of the ground level are similar to those of the fine-grained soils, but the values are obviously much lower: for crushed gravel embankments they vary between 0.3 and 16.0 cm, while for "pozzolana" embankments vary between 0.2 and 12.0 cm, with a 25% reduction in final settlements.

The settlements due only to the deformation of the materials constituting the embankments prove to be negligible in relation to the corresponding ones of the ground level, being 0.3 cm at the maximum for the crushed gravel embankments, and 0.6 cm for the "pozzolana" ones. It seems clear that the total settlements at the top of the embankments mainly depend on the stiffness of the subsoil layer, given the high stiffness values of the embankments obtained by means of the usual construction techniques.

With regard to the finite element method, this was applied to most of the cases examined. Here a comparison is shown between the two approaches (FEM and the approximated one) only for the heaviest case considered. With reference to the most compressible NC subsoil (E_o =15 MPa and E_{ed} =5 Mpa) and to crushed gravel embankments, the final settlements (w_f) of the ground level are represented in Figure 6. It may be evinced that the

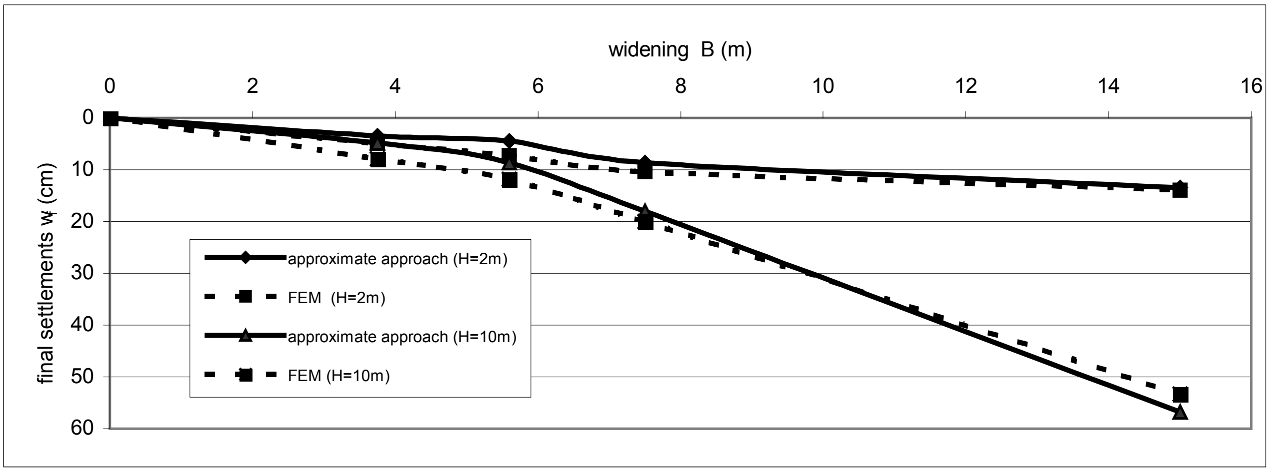

Figure 6 - Normal consolidated NC fine-grained subsoil (E_o =15 MPa, E_{ed} =5 MPa): comparison between the final maximum settlements (w_f) of the ground level by means of the FEM approach and the approximate one.

final maximum settlements of the ground level obtained with the two approaches are practically congruent with each other. Similar results have been found in all the cases studied.

5. ANALYTICAL RELATIONSHIPS FOR THE ASSESSMENT OF THE MAXIMUM SETTLEMENTS

Regarding what was envisaged in Paragraph 2, the maximum settlement due to the new embankment was taken as the representative parameter of the behaviour of the embankment itself. Hence arises the need to identify a simple and efficacious method for the direct assessment of this settlement. For this purpose regression analyses of the results obtained were carried out, by selecting analytical functions which correlate the maximum ground-level settlement with the geometrical and mechanical characteristics of the system:

$$w = a \bullet B^2 + b \bullet B \quad (8)$$

where:

w (cm) represents for the fine-grained soils the immediate settlement (w_o) or the consolidation one (w_c), while for the coarse-grained soils is the final settlement (w_f), B is the widening in metres, (a) and (b) are the regression coefficients, function of the height H of the embankments and of the soil modulus, as well as of the unit weight of the embankment material.

In the regression analyses B ranges between 3.75 and 15.0 m, the height H of the embankments is between 2 and 10 m, for the fine-grained soils the modulus E_o ranges between 15 and 30 MPa and E_{ed} between 5 and 20 MPa, while for the coarse-grained soils E_{ed} ranges between 20 and 75 MPa.

In Tables 1 and 2 the values of coefficients (a) and (b) to be introduced into equation (8) are reported, in function of the modulus of the soil, the height and the material of the embankment. For clarity of display such coefficients are indicated for fine-grained soils with the symbols (a_o, b_o) ed (a_c, b_c) respectively for the calculation of the immediate settlements and the consolidation ones. The correlation coefficient R^2 obtained proved to be between 0.90 and 0.99 for all the cases examined.

To give an example, with reference to the fine-grained soils and crushed gravel embankments, the immediate settlements w_o of the ground level are deduced as follows:

a) $w_o = a_o \bullet B^2 + b_o \bullet B = [\ 0.0558 \bullet (15)^2 + 0.1436 \bullet (15)\ ] = 14.7$ cm

b) $w_o = [0.0014 \bullet (3.75)^2 + 0.1024 \bullet (3.75)] = 0.4$ cm

respectively in the cases of:

a) B=15 m, H =10 m and E_o =15 MPa (example of normal consolidated subsoil),

b) B=3.75 m, H=2 m and E_o =30 MPa (example of over-consolidated subsoil).

Such values are practically coincident with those found with the approximate approaches (see paragraph 4), which provided immediate settlements of 14.5 cm and 0.4 cm, respectively. The corresponding maximum consolidation settlements w_c are for the two above-mentioned cases, respectively:

a) $w_c = [0.1580 \bullet (15)^2 + 0.4486 \bullet (15)] = 42.3$ cm

b) $w_c = [-0.0019 \bullet (3.75)^2 + 0.1882 \bullet (3.75)] = 0.7$ cm; these values practically coincide with those calculated by the approximate approaches, being equal to 42.0 cm and 0.5 cm, respectively. By and large, the final settlements w_f for the fine-grained soils obtained with these ratios prove to be between 1.1 and 57.0 cm, compared with $w_f = 0.9 \div 56.5$ cm calculated by the approximate approaches.

Regarding "pozzolana" embankments immediate settlements w_o between 0.4 and 11.3 cm were deduced, while the approximate approaches gave respectively 0.3 and 11.3 cm; consolidation settlements w_c between 0.5 and 30.4 cm were derived (against $0.4 \div 30.2$ cm calculated previously).

Finally, with regard to the coarse-grained soils, the relationships provided settlements w_f between 0.3 and 15.8 cm and between 0.2 and 12.2 cm for the crushed gravel and the "pozzolana" embankments respectively; $w_f = 0.30 \div 16.0$ cm and $w_f = 0.2 \div 12.0$ cm were calculated respectively by the approximate approaches.

Table 1 – Fine-grained soils: regression analysis coefficients (a_o) and (b_o) for the evaluation of immediate w_o settlements; (a_c) and (b_c) coefficients for the evaluation of consolidation w_c settlements.

	$w = a \bullet B^2 + b \bullet B$							
	Normal consolidated NC fine-grained soil							
	Crushed gravel embankment				"Pozzolana" embankment			
	E_o =15 MPa		E_{ed} =5 Mpa		E_o =15 MPa		E_{ed} =5 MPa	
H(m)	a_o	b_o	a_c	b_c	a_o	b_o	a_c	b_c
2	-0.0049	0.2894	-0.0039	0.7505	-0.0051	0.2574	-0.0091	0.6677
3	-0.0056	0.3829	-0.0132	1.0855	-0.0046	0.3147	-0.0128	0.9249
5	-0.0015	0.4989	0.0445	0.9758	0.0072	0.3111	0.0209	0.8546
10	0.0558	0.1436	0.1580	0.4486	0.0389	0.1719	0.0937	0.6183
	E_o =17 MPa		$E_{ed,}$ =6 Mpa		E_o =17 MPa		$E_{ed,}$ =6 MPa	
H(m)	a_o	b_o	a_c	b_c	a_o	b_o	a_c	b_c
2	-0.0026	0.2351	-0.0033	0.6263	-0.0041	0.2276	-0.0076	0.5563
3	-0.0036	0.3277	-0.0111	0.9057	-0.0034	0.2764	-0.0107	0.771
5	0.006	0.3461	0.0372	0.8115	0.0084	0.2569	0.0175	0.7119
10	0.0521	0.1142	0.1307	0.3891	0.0368	0.1173	0.0781	0.5153
	E_o= 20 MPa		E_{ed}, = 7.5 Mpa		E_o= 20 MPa		E_{ed}, = 7.5 MPa	
H(m)	a_o	b_o	a_c	b_c	a_o	b_o	a_c	b_c
2	-0.0033	0.2162	-0.0049	0.4608	-0.0033	0.1875	-0.006	0.4453
3	-0.003	0.2764	-0.0104	0.6507	-0.0031	0.2398	-0.0085	0.6167
5	0.0061	0.2862	0.0237	0.5564	0.0064	0.2297	0.014	0.5693
10	0.0455	0.0803	0.086	0.2753	0.0306	0.1293	0.0624	0.4128
	Over-consolidated OC fine-grained soil							
	E_o= 25 MPa		E_{ed} = 10 Mpa		E_o= 25 MPa		E_{ed} = 10 MPa	
H(m)	a_o	b_o	a_c	b_c	a_o	b_o	a_c	b_c
2	-0.0008	0.1523	-0.0039	0.3770	-0.0007	0.1261	-0.0037	0.3069
3	-0.001	0.2114	-0.0076	0.5309	-0.0011	0.1788	-0.0027	0.3881
5	0.0027	0.2768	0.0309	0.3611	0.0057	0.1892	0.01	0.3798
10	0.0339	0.1292	0.0696	0.2121	0.0293	0.0546	0.04	0.2975
	E_o = 27 MPa		E_{ed} = 15 Mpa		E_o = 27 MPa		E_{ed} = 15 MPa	
H(m)	a_o	b_o	a_c	b_c	a_o	b_o	a_c	b_c
2	0.0005	0.1267	-0.0026	0.2508	0.0004	0.105	-0.0025	0.2043
3	0.0016	0.1665	-0.0065	0.3769	-0.0002	0.1604	-0.0019	0.2545
5	0.0056	0.2268	0.0229	0.2051	0.0067	0.1659	0.0067	0.2535
10	0.033	0.1198	0.0475	0.1252	0.0256	0.0948	0.0267	0.1984
	E_o =30 Mpa		E_{ed} =20 Mpa		E_o =30 MPa		E_{ed} =20 MPa	
H(m)	a_o	b_o	a_c	b_c	a_o	b_o	a_c	b_c
2	0.0014	0.1024	-0.0019	0.1882	-0.001	0.1194	-0.0019	0.1537
3	0.0007	0.1672	-0.0042	0.2718	-0.0004	0.1525	-0.0013	0.1899
5	0.0096	0.1681	0.0171	0.154	0.0059	0.1588	0.005	0.1896
10	0.0319	0.0998	0.0337	0.123	0.0229	0.0986	0.02	0.1492

Table 2 – Coarse-grained soils: regression analysis coefficients (a) and (b) for the evaluation of the final w_f settlements.

	$w = w_f = a \bullet B^2 + b \bullet B$							
	Coarse-grained soil							
	Crushed gravel embankment				"Pozzolana" embankment			
	E_{ed} =20 MPa		E_{ed} =25 Mpa		E_{ed} = 20 MPa		E_{ed} = 25 MPa	
H(m)	a	b	a	b	a	b	a	b
2	-0.0057	0.305	-0.0045	0.244	-0.004	0.2479	-0.0032	0.1983
3	-0.0073	0.4325	-0.0049	0.3325	-0.0069	0.3612	-0.0054	0.2925
5	0.0058	0.4811	0.0047	0.3849	0.0056	0.3584	0.0045	0.2866
10	0.054	0.2436	0.0437	0.1882	0.0378	0.2432	0.0306	0.1889
	E_{ed} =30 MPa		E_{ed} =50 Mpa		E_{ed} =30 MPa		E_{ed} =50 MPa	
H(m)	a	b	a	b	a	b	a	b
2	-0.0038	0.2033	-0.0023	0.122	-0.0027	0.1653	-0.0016	0.0992
3	-0.0041	0.2771	-0.0024	0.1662	-0.0045	0.2438	-0.0027	0.1463
5	0.0039	0.3207	0.0023	0.1924	0.0037	0.2389	0.0022	0.1434
10	0.0364	0.1569	0.0218	0.0941	0.0255	0.1574	0.0153	0.0944
	E_{ed} =60 MPa		E_{ed} =75 Mpa		E_{ed} =60 MPa		E_{ed} =75 MPa	
H(m)	a	b	a	b	a	b	a	b
2	-0.0019	0.1017	-0.0015	0.0811	-0.0013	0.0827	-0.001	0.0647
3	-0.002	0.1385	-0.0016	0.1108	-0.0023	0.1219	-0.0018	0.0975
5	0.0019	0.1604	0.0017	0.1264	0.0019	0.1195	0.0015	0.0955
10	0.0182	0.0785	0.0145	0.064	0.0128	0.0788	0.0102	0.063

With appropriate interpolations these ratios may also be utilized for an approximate estimation of the maximum settlements in further cases in which the parameters are in the range of the values here examined.

6. SUBSOIL IMPROVEMENT TECHNIQUES

The functionality of the infrastructure following the cross-section road widening is obviously influenced by the values of the ground level settlements and by their evolution through time. The immediate settlements (w_o) occur on completion of works, so that what concerns us here is the development of the consolidation settlements (w_c) alone. An approximate assessment of such consolidation time (Caliendo and Simonelli, 2002) has shown that the settlements w_c develop quite rapidly in the early years and then increase more slowly through time. For example, after 20 years (corresponding to the average life time of a road pavement), settlements are generally greater than 50 % of the total consolidation value. Therefore if the latter is of a considerable amount (e.g. in the case of poorer soils, high embankments and large widening) the evenness of the wearing course might be compromised even just a short time after opening the road to traffic; hence reducing the safety and comfort of circulation. In such cases it is necessary to implement engineering techniques for reducing the effects of the ground-level consolidation settlements.

Several techniques may be carried out, depending on the soil characteristics and on the thickness of the compressible subsoil layer. The more widespread techniques are those consisting in employing pre-loadings and/or drainages (sand piles or prefabricated drains) (Lambe et al., 1969; Rodriguez et al., 1988; Lancellotta, 1993; Jappelli, 1996; Yeung, 1997; ASCE, 1997; AIPCR/PIARC, 2001) or jet-grouting consolidations (Lunardi, 1992; La Banca, 2000). One of the more innovative techniques consists in the reduction in ground-level loads, employing light material for the construction of the new embankment, such as expanded clay (Bowders et al., 1997; Caraffa, 1999; Di Prisco, 2001) or expanded polystyrene (Magnan et al., 1985; AIPCR/PIARC, 2001; Montepara et al., 2001).

With the pre-loading technique, prior to constructing the new embankment, an appropriate provisional load has to be left at ground-level until the degree of soil consolidation attains the desired effect. However, for the low permeability of the fine-grained soils, the consolidation time would be too long, hence a drainage system should be provided.

Drainage systems have to be sub-vertical, since they must act both in the subsoil under the new embankment and the pre-existing one. Drains are usually classified into sand drains and prefabricated drains. With reference to the installation technique, they may be further classified into driven drains or vibro-driven drains without earth removal, and drains made by drilling and earth removal or by hydraulic-type boring (jetting). Drains realised by driving, beating or vibration, may cause great disturbance to soils, such as reduction in both shearing resistance and permeability (e.g. when the macrostructure is destroyed); in the former case stability problems may arise, while in the latter consolidation times increase.
With drains made through drilling and material removal the considerable horizontal deformations of the soil surrounding the bore-hole are avoided, whereas the problems caused by its rearrangement remain. With the “jetting-type” drains the bore-hole perforation is realised by means of pressurised water, thus containing the above-mentioned limits; nevertheless a series of controls is required in order not to invalidate the efficacy of the installation.

Prefabricated drains offer the advantages of a faster and less expensive installation, compared to sand drains. In general they have a plastic hard core, which allows water-draining. The plastic core is generally provided with an external woven non-woven or treated paper, at the aim to prevent the drain from being blocked up by fine soil grains. They may be installed dynamically (by beating a mandrel which contains the drain) or statically (by a pushing equipment); the water pressure generated during the installation phase obviously differs according to the technique.

With the jet-grouting technique, which has to be realised both in the subsoil under the new embankment and the pre-existing one, the mechanical behaviour of the soils would be directly improved by reducing its compressibility and increasing its shear strength. As known, this technique consists of injecting into the subsoil pre-fixed amounts of high-pressure and high-velocity cement mix, by means of small-sized perforations. The injected fluid disintegrates the soil skeleton in the hole surroundings; the soil particles first mix with the injected fluid and then transform into a bonded material. Thus with this technique, more or less cylindrical volumes of bonded soil are created (consolidated columns), whose diameter is a function of the soil grain size distribution and of the work procedure. The main problem connected to this technique consists in the variability of the stiffness characteristics of the consolidated soils, due to the eventual heterogeneity in the propagation of the injected fluid (claquage).

The implementation of a lightened new embankment would reduce the extent of the ground level settlements, having applied lower intensity loads. This technique may be eventually associated with the replacement of a soft surface soil layer (compensated technique). In such case the replacing material is characterised by good mechanical properties and eventually by a low unit weight, which can compensate, either partially or completely, the overload of the new embankment that is to be built. One of the new light materials which could be utilised for the embankment is the expanded clay. The lightness of this material ($\gamma_s = P_s/V = 3 \div 5$ kN/m^3) is due to the fact that inside the individual grains a considerable amount of voids is present, some of which are not interconnected. Since the surface of each grain is almost impermeable, the internal voids are hardly accessible to the pore water. One of the main problems of the embankments in expanded clay consists in an adequate laying of such material. In fact excessive compaction, as well as the action of the roller may cause a marked increase in the percentage of crushed clay, hence bringing about both the increased weight of the material, because of the variation in the grain size distribution, and the risk of a huge amount of water being absorbed. Thus provision is made for the expanded clay to be realized in successive layers, according to an appropriate procedure. Usually a first geotextile is placed on the surface ground, with the aim of preventing the voids between the expanded clay particles from being penetrated by the fine-grained soils. Hence each layer of expanded clay (e.g. about 60 to 80 cm in thickness, according to the practice in Italy) is covered by a layer of well-graded aggregate (e.g. between 20 and 30 cm in thickness, according to the practice in Italy). Between them a geotextile is placed, in order to prevent the two materials mixing. Above the well-graded aggregate, compaction is realised by means of a light dynamic roller. Provision is made for the slopes of the embankment to be covered with a layer of well-graded aggregate (thickness in the order of 30 to 50 cm) to prevent the surface erosion of the expanded clay induced by streaming water. The slope angle does not generally exceed 33°, taking into account the friction angle of this material.

A further technique for the realization of a light embankment consists in the use of expanded polystyrene (EPS). This material was introduced only a few years ago, and thus it is still at the experimental stage. It is placed in single blocks of a very light unit weight (between 0.2 and 0.4 kN/m^3), thus presenting a large floating capacity even though they are practically impermeable. The material is homogeneous, isotropic and on compression shows an elasto-plastic-hardening behaviour. In order to limit creep phenomena, international experience imposes the control of the strain-stress state. The embankment is made up through layers of prismatic EPS blocks realized by staggering the joints; in order to avoid the sliding and to ensure the distribution of stresses, the blocks are joined together by means of toothed plugs in metallic material (grippers). In view of the material's low unit weight, it is necessary to avoid any interference with the ground water, which could cause the floating of the blocks; for this purpose a drainage system is thus to be provided. Furthermore the EPS embankment is to be protected from the streaming water too, for example by covering the slopes with vegetable soils. EPS is more expensive than other materials traditionally used in embankments; nevertheless it produces indirect economical benefits, since it facilitates moving the blocks in the building site (without the utilization of mechanical equipments) and a shorter construction time. Furthermore with EPS it is possible to create steeper slopes, which means less encumbrance.

The embankments employing light material (expanded clay or EPS) generally require the construction of a stiffer road pavement to ensure a wider distribution of the stresses induced by the traffic loads. For this it would be necessary, for example, to make provision for the use of continuously reinforced concrete, which also could be utilised as a foundation for the safety barriers.

Among the techniques presented above, those based on light materials are currently arousing considerable interest. In fact this solution proves to be less expensive and requires shorter construction time, compared with those which are based on draining systems for reducing the time of consolidation settlements, and on jet-grouting for the direct improving of soil mechanical proprieties. Thus in the present work it has been examined the solution in light material; in particular expanded clay has been chosen, since some embankments have already been realised with this material in Italy.
To assess the efficacy of the solution proposed, a comparison was performed between settlements induced by different embankment materials (crushed gravel and “pozzolana”).

7. ANALYSIS OF THE CONSOLIDATION SETTLEMENTS INDUCED BY THE NEW EMBANKMENT IN EXPANDED CLAY AND RELATIVE COMPARISONS

The results of the calculation of the maximum consolidation settlements w_c, due to the weight of the new embankment in expanded clay, are represented in apposite diagrams in function of H and B, for a given value of the aedometric modulus (E_{ed}) of the fine-grained soil. To exemplify, with reference to the cases of softer and stiffer subsoils (respectively E_{ed} = 5 MPa for NC soils and E_{ed} = 20 MPa for OC soils), the results relating to the embankments of greater heights (H = 5 m and H = 10 m) are reported in Figures 7 and 8. In order to perform an effective comparison, in the same figures the consolidation settlements related to crushed gravel and “pozzolana” are reported.
The diagrams show that the consolidation settlements have similar trends for all three types of materials (i.e. they increase with H and B, while they decrease with E_{ed}); on the other hand w_c values relating to expanded clay are notably smaller. With reference to the totality of the cases studied, in synthesis it was found that for expanded clay the consolidation settlements w_c are between 0.13 and 8.1 cm, against w_c =0.5÷42.0 cm and w_c = 0.4÷32.0 cm induced by the crushed gravel and “pozzolana” respectively. Thus by utilising this light material reductions in the consolidation settlement of the order of 75-80% of the crushed gravel one, and of 70-75% with respect to “pozzolana”, are obtained.

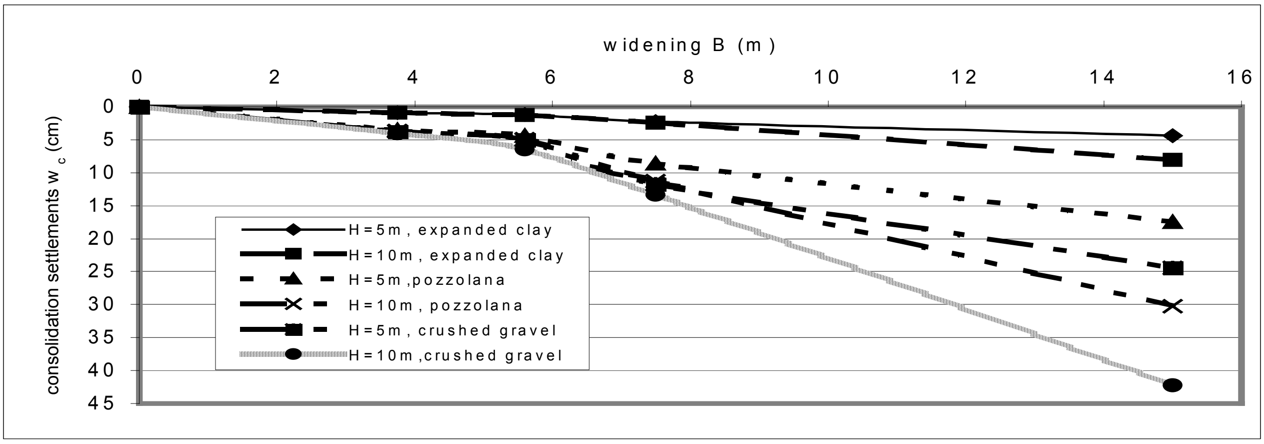

Figure 7 – Fine grained normal consolidated subsoil (E_{ed} =5 MPa): comparison between the ground level consolidation settlements (w_c) induced by the new embankment in expanded clay, crushed gravel and "pozzolana".

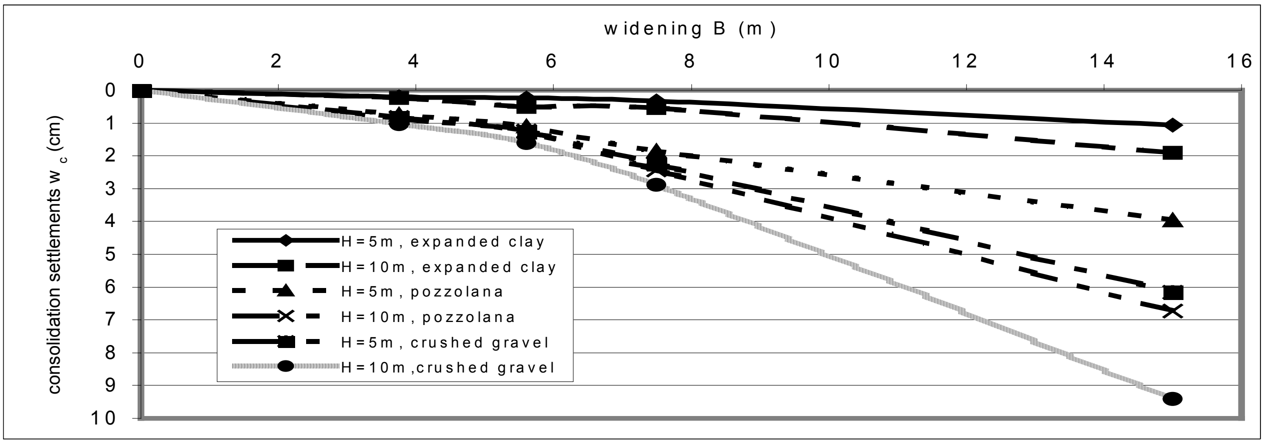

Figure 8 – Fine grained over-consolidated subsoil (E_{ed} = 20 MPa): comparison between the ground level consolidation settlements (w_c) induced by the new embankment in expanded clay, crushed gravel and "pozzolana".

In order to estimate the overall benefit on the functionality the infrastructure undergoing widening, the comparison would be made in reference to the total settlements of the road surface. Hence besides the computed settlements (due to the stiffness of the subsoil) the ones due to the stiffness of the embankment material caused by travelling vehicles and the viscous settlements of the pavement materials should be considered. It must be pointed out that for the assessment of these further settlements, which are not object of this study, the methodology generally followed makes use of the stresses caused by the traffic in the laws of accumulation of the permanent deformations under dynamic loads. The above-mentioned stresses are obtained through the resolution of the multi-layered elastic system made up of the pavement and the embankment, the latter resting on a non-compressible support.

In order to provide a simple method for directly assessing the maximum consolidation settlement w_c of the ground level, also for the expanded clay, regression analyses of the w_c results were carried out. In Tables 3 the corresponding values of the correlation coefficients (a_c) and (b_c) to be introduced into equation (8) are reported, in function of the modulus E_{ed} of the soil and the height H of the embankment. The relationships proposed provide the following values of w_c:

Table 3 - Fine-grained soils: regression analysis coefficients a_c and b_c for the evaluation of consolidation w_c settlements due to the weight of the new embankment in expanded clay.

	$w = w_c = a \bullet B^2 + b \bullet B$					
	New embankment in expanded clay					
	Normal consolidated (NC) fine-grained soil					
	E_{ed} =5 MPa		E_{ed} =6.5 MPa		E_{ed} = 7.5 MPa	
H(m)	a_c	b_c	a_c	b_c	a_c	b_c
2	-0.0021	0.1688	-0.006	0.1334	-0.0006	0.1091
3	-0.0032	0.231	-0.0004	0.1643	-0.0007	0.1402
5	0.0043	0.2287	0.0088	0.1437	0.0118	0.0905
10	0.0302	0.0843	0.0257	0.0649	0.0206	0.062
	Over-consolidated (OC) fine-grained soil					
	E_{ed} = 10 MPa		E_{ed} =15 MPa		E_{ed} = 20 MPa	
H(m)	a_c	b_c	a_c	b_c	a_c	b_c
2	-0.0015	0.087	0.0017	0.0289	0.0006	0.0234
3	-0.0007	0.0949	0.0008	0.0461	0.0011	0.028
5	0.0029	0.0887	0.0032	0.0435	0.003	0.0’259
10	0.012	0.0573	0.01	0.0145	0.0071	0.0205

a) w_c= $[0.0302 \bullet (15)^2 + 0.0843 \bullet (15)]$ = 8.1 cm
b) w_c= $[0.0006 \bullet (3.75)^2 + 0.0234 \bullet (3.75)]$ = 0.10 cm;
respectively in the cases of:
a) B =15 m, H =10 m and E_{ed} =5 MPa (example of normal consolidated soil),
b) B=3.75 m, H=2 m and E_{ed} =20 MPa (example of over-consolidated soil).
The values found are practically equal to those obtained by the calculation methods (w_c=8.1cm and w_c=0.13 cm).

8. CONCLUSIONS

Both immediate (w_o) and consolidation (w_c) ground level settlements, due to the weight of the new embankment, increase with both the widening (B) and the height (H) of the embankments, while they decrease with the soil modulus (E_o or E_{ed}).

For crushed gravel embankments and fine-grained subsoils immediate maximum settlements (w_o) of the ground level between 0.4 and 14.5 cm have been computed, while the consolidation ones (w_c) are found between 0.5 and 42.0 cm, to which final settlements (w_f) between 0.9 and 56.5 cm correspond. If the pre-existing and the new embankments are made of “pozzolana”, lower settlement values are found; in particular the reduction for the final settlement is of the order of 20-25%. In the case of coarse-grained subsoils, for the range of stiffness values considered, maximum final settlements of the ground-level turn out to be considerably smaller than those of fine-grained soils, being approximately between 0.3 and 16.0 cm. In this case too the use of “pozzolana” instead of crushed gravel causes a reduction in the settlements of about 25%.

Settlements due to the deformations of the material making up the embankments (“pozzolana” and crushed gravel), caused by their own weight, prove to be negligible compared to ground-level settlements, being at maximum 0.3 cm for crushed gravel and 0.6 cm for “pozzolana” embankments.

A finite element approach, for the resolution of which an appropriate calculation code has been used, has shown that settlements obtained with this method are congruent with those produced by approximate and more simple approaches, which implement the traditional methods of Skempton and Bjerrum for the fine-grained soils and aedometric for coarse-grained ones.

Regression analyses of the obtained results allowed to find out analytical relationships that provide a direct estimation of the maximum settlements of the ground level, in function of the geometry of the embankment-subsoil system and of the mechanical properties of materials.

Among the techniques for reducing consolidation settlements w_c and their effects on the serviceability of the road infrastructure, those based on the utilization of light materials appear to be economically advantageous and less time-consuming, compared to those based on the drainage of the pore water and on the direct improvement of subsoil proprieties.

Among this light materials, expanded clay embankments, produce maximum ground-level consolidation settlements between 0.13 and 8.1 cm. These values are much lower than those induced by the same size crushed gravel and “pozzolana” embankments (about 75-80% and 70-75% respectively).

In conclusion, the use of expanded clay implies significant reductions of ground level settlements; nevertheless this technique still presents open problems, which are basically related to the laying procedures and/or to potential interference with phreatic and/or streaming water, as well as to the stress state induced by vehicles and to the to the long-term performance. It is therefore to be hoped that in the next future studies and experimental investigations are orientated towards a better understanding of these problems, the solution of which would encourage a more extensive utilization of such material for embankment widening.

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