Lightweight Highway Embankments to solve the “Underground Dam Effect”

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Synopsis

In previous studies, the author highlighted the way in which the construction of a road embankment can modify the stress state of supporting ground, its permeability and hence groundwater level, causing the “underground dam effect”, in particular circumstances.
A model has been developed to determine ground stress state and, to analyse it, a finite element method has been used with the support of ANSYS® software. The model has been parameterized for ground slope, embankment size width, half roadway size and slope size width and, finally, for embankment height. The software has provided horizontal and vertical stress distribution. Void index has been determined through the compressibility curve and also the permeability for each element. Subsequently, the groundwater level trend was reconstructed after fixing the flow and forward groundwater depth.
Various cases have been examined: changing ground characteristics, embankment height, ground slope and finally changing groundwater depth, and critical situations have been identified.
In this study the author shows the way in which the utilization of expanded clay or geofoam applications in highway embankments could solve the “underground dam effect” and hence allow infrastructure insertion in the territory causing minimum hydrologic impact.
Indeed, infrastructure design must target durability during useful life, preserving land balance and guaranteeing preservation of the environmental conditions existing before road construction

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Previous studies published by the same author [Coni M., Maltinti F., Saba A., Portas S., Annunziata F.(1998); Maltinti F. (2002); Annunziata F., Coni M., Maltinti F., Pinna F., Portas S., (2004)], highlighted the fact that the creation of a highway embankment leads to modification of the hydrologic conditions of the foundation terrain where a groundwater is present. Indeed, the weight of the embankment determines modification in stress factors and permeability of the underlying ground and, in the presence of a groundwater, this leads to an increase in groundwater level and in some cases to its coming to the surface above ground level. This effect known as “the underground dam effect” has been studied using a finite element model simulating the behavior of a portion of terrain of 90 m subjected to the weight of an embankment of variable height.

ANALYSIS METHODS

Analysis was carried out by addressing a portion of terrain of differing mechanical characteristics, 90 m long with variable ground surface slope and depth of rocky strata. On this a highway embankment of varying height was constructed.

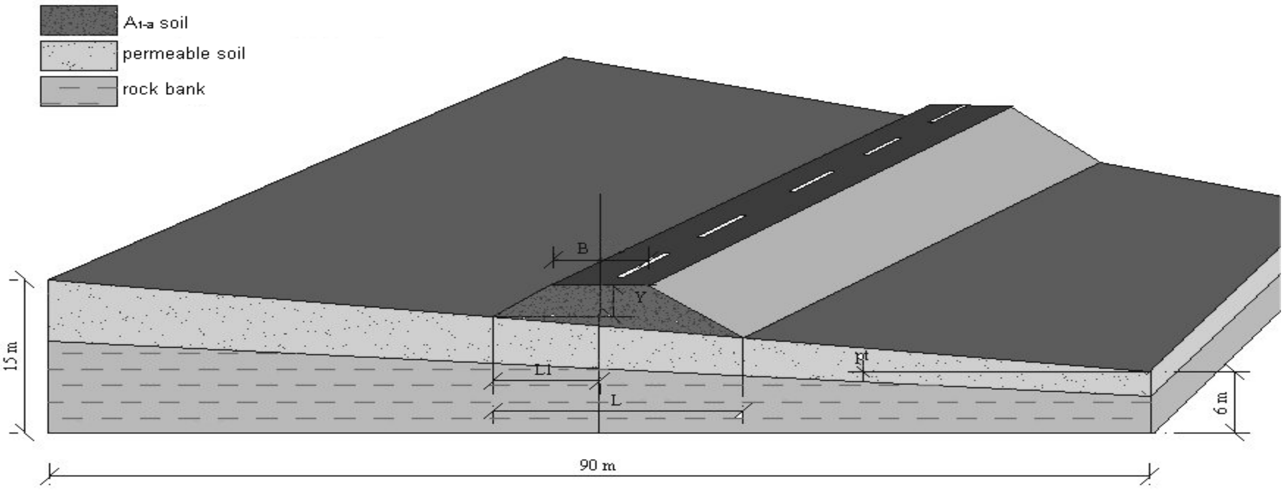

Figure 1: The model in one of the cases considered

In the following table lists the magnitudes varied in order to make the model versatile and applicable to any real case scenario.

Table 1: Values attributed to variable magnitudes

p_t = surface slope	5%	10%	15%							
p_v = depth of rocky stratum measured downstream from the model [m]	-6	-5.4	-4.8	-4.2	-3.6	-3,0	-2,4	-1,8	-1,2	-0,6
y = embankment height [m]	4	8	12	16						
h_v = depth of downstream groundwater (starting from run-off plane) [m]	0.5	0.8	1.1	1.2	1.5					

The assumption was made that the soil forming the embankment belonged to group A1 with a Young’s Modulus (E) of 1×10^8 N/m^2, a Poisson’s ratio (ν) of 0.4 and finally density (ρ) of 2000 kg/m^3.

Two types of soil with different permeability (A and B) forming the embankment support terrain and through which flows the groundwater were examined. Table 2 shows the mechanical characteristics of the two types of soil.

Furthermore it was assumed that the stratum of permeable soil rested on a stratum of mica-schist of considerable rigidity (E = $79,3\times10^9$ N/m^2) which was also considered to be the flow plane of the water table.

Table 2: Mechanical characteristics of the soils forming the embankment support terrain

TYPE OF SOIL	MECHANICAL CHARACTERISTICS		
	E	ν	ρ
Soil A	0.8×10^{8} N/m^2	0.45	1800 kg/m^3.
Soil B	0.8654×10^{7} N/m^2	0.38	2650 kg/m^3.

After model conceptualization, the domain was discretized into 900 elements which form the bed and 10 elements for L (overall embankment width: varying as a function of height), which make up the road embankment itself (figure 2).

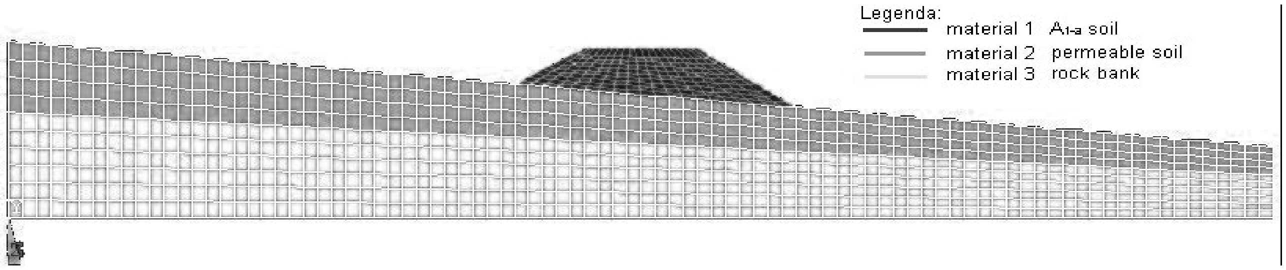

Figure 2: Model discretization in one of the cases examined

To study the stress status of the foundation soil induced by the weight of the embankment, Finite Element Method and ANSYS ® Software was utilized. Element Plane 42, used for modeling solid structures in two dimensions, was chosen.

In this way, it was possible to obtain stress values for each element and therefore obtain void index values utilizing the 'in situ' compressibility curves obtained from the edometric curves.

Once the void index for each element had been obtained, permeability was determined using Taylor's equation [Lambe T.W., Whitman R.V.(1997)]:

$$k = D_s^2 \frac{\gamma}{\mu} \frac{e^3}{(1+e)} C$$

where:

k = permeability coefficient according to Darcy;

D_s = effective soil particle diameter;

γ = specific gravity of permeating fluid;

μ = viscosity of permeating fluid;

e = void index;

C = shape factor.

Permeability values were averaged to obtain a single permeability value for each element column.

Filtration capacity Q (unitary capacity) was estimated using the following relation:

$$Q = k_{ind}\, jA$$

where:

$$V = k_{ind}\, j$$

with

k_{ind} = soil permeability coefficient without infrastructure ("undisturbed");

j = head loose;

V = speed;

A = groundwater cross-section area.

Finally, since filtration consistency is expressed by the following equation [CITRINI, G. NOSEDA (1982)]:

$$Q = k_m \frac{(h_m - h_v)}{\Delta x} A$$

where:

Q = filtration capacity;

k_m = mean permeability;

h_m = height of groundwater level upstream;

h_v = height of groundwater level downstream;

Δx = increment of the abscissa (= 1 m);

A = area of water table cross-section;

and the only unknown is the upstream height of the groundwater (h_m), since downstream height (h_v), as already mentioned, was established arbitrarily, point plotting of the groundwater profile changes for each case under examination could be performed.

RESULTS OBTAINED

The most important results of analyses performed in preceding studies are summarized below, enabling subsequent comparison with results obtained using alternative materials to construct light embankments.

The situation shown in Figure 3 is the most critical scenario in the case of soil type A (more permeable than B), since:

- The foundation soil is supporting a significantly large embankment (y = 16 m);
- The groundwater flow plane is relatively close to the surface (p_v = -0.6 m);
- Downstream height of the groundwater level is 10 cm from ground surface (h_v = 0.5 m measured from the flow plane).

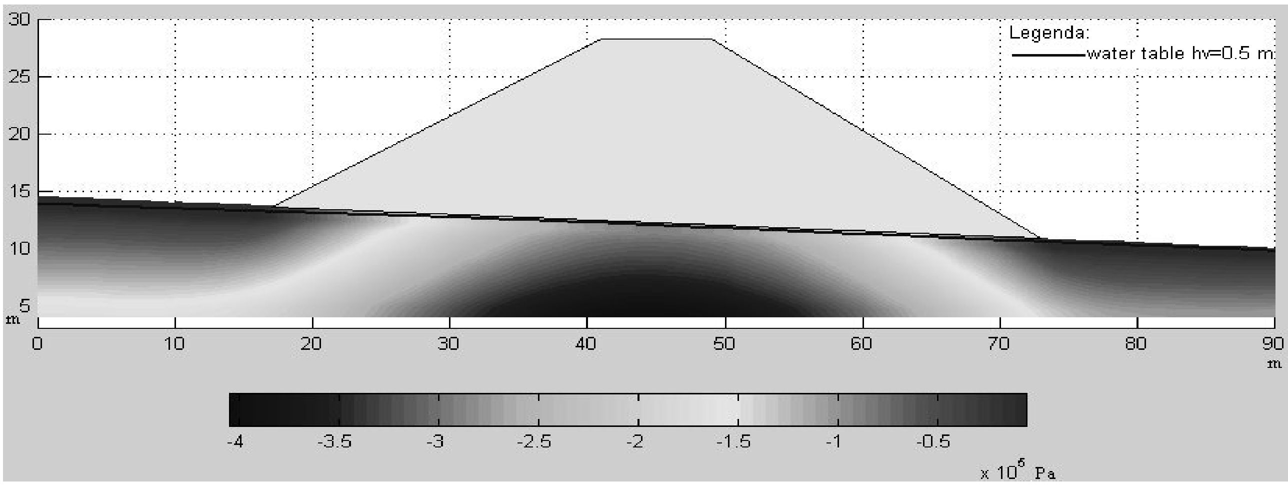

Figure 3: Trend of groundwater level (type A soil) – critical situation

Notwithstanding these conditions, no flooding from groundwater took place, although in correspondence with the embankment mass, a rise in the groundwater level of a few cm was noted. However, this produced no effects on terrain hydrology since upstream and downstream, the table followed its natural trend.

The situation is quite different if the embankment is based on a lower permeability soil.

Indeed, in this case, an increase in groundwater level significantly higher than in the case quoted above was generally found, with all other variables being equal. What is more, groundwater flooding was noted, even in conditions which were not particularly critical, such as:

- Embankment height y = 4 m;
- Depth of rocky stratum p_v = -1.80 m;
- Downstream groundwater depth h_v = 0.5 m starting from flow plane.

In this case, illustrated in Figure 4, there was a maximum rise of 2.30 m and surface flooding extending for about 5 m in the vicinity of the upstream embankment slope.

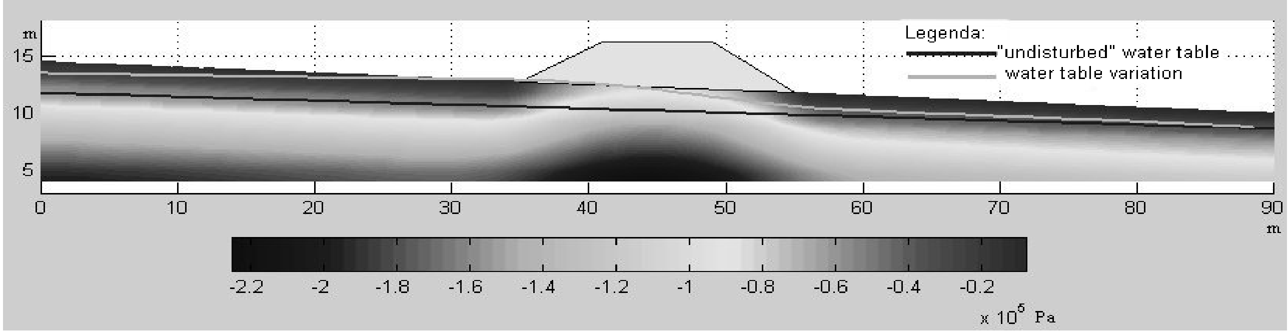

Figure 4: Groundwater level trend (soil B type) – critical situation

USE OF LIGHTWEIGHT MATERIALS IN ROAD CONSTRUCTION

The use of lightweight embankment fill materials for road construction affords significant reduction in the weight of the embankment and consequently of the load imposed on foundation soil, thus maintaining almost unchanged the original stress balance. Adoption of the “load compensation” technique offers several advantages:

- Once the construction and compacting phase has been completed, the lightweight embankment reduces absolute and differential settlement to a considerable extent;
- Use increases significantly the safety coefficient assessed with reference to ultimate limit state of the embankment;
- The compensated load solution does not require preloading;
- The use of alternative lightweight fills makes it possible to avoid recourse to more time-consuming and costly construction techniques.

Lightweight road construction techniques developed in recent years are based on the use of purpose-made products (Expanded Polystyrene EPS, expanded clay, steel pipes, lightweight concrete), industrial process by-products (ash and blast furnace slag) and recycled materials (tire fragments, wood fiber, fly ash, crushed cement). Table 3 hereunder shows the characteristics of these materials [Biasuzzi K., Marinelli M., Vignali, V. (2004)].

Table 3: Characteristics of materials most commonly used for the construction of lightweight embankments

MATERIAL	DENSITY (kg/m^3)	RESISTANCE TO COMPRESSION (KPa)	YOUNG’S MODULUS (KPa)
EPS	10÷40	100÷300 al 10% deformation	6.5×10^{3}
Expanded clay	<450 in a heap 600 tamped	1.2×10^{3}	4×10^{4}
Wood fiber	720÷860	$10 \div 12 \times 10^{6}$	$10 \div 12 \times 10^{6}$
Fly ash	1200÷1700	1.2×10^{3}	$10 \div 11 \times 10^{6}$
Tire fragments	320÷530 loose 720÷900 loose	Resistance to cutting ≅42 kPa with □=80kPa	350÷820

Expanded Clay

Recently there has been widespread use of expanded clay in the creation of embankments on soft soils such as inorganic soft clay, compressible silt, organic clay and peat [Lo Prisco, Luisi (2001)].

Expanded clay is both a natural and an artificial material, since it is obtained by means of heat processing starting from natural clay. The single grain consists of an external shell which is extremely resistant and poorly porous, whereas the internal portion has a high void index.

Some of these voids are interconnected and thus easily saturable when this material is placed under the groundwater, and they are defined as ‘inter-granular’; whereas the intra-granular pores are resistant to filling with water and never become completely saturated. The presence of these voids means that this material’s specific weight is four times less than, for example, that of natural sand.

Exploiting this significant weight reduction when speaking of an embankment (in the region of 1t/m^3) it is possible to perform many types of works using the load compensation method. This method makes it possible to construct the embankment while keeping loads on the terrain to a minimum, thus maintaining the original stress balance status unchanged.

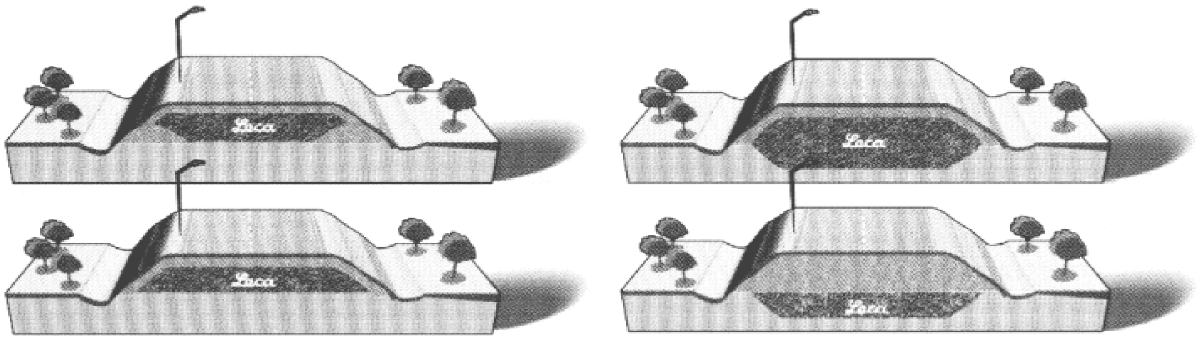

Figure 5: Various types of light embankments [Leca].

Figure 5 shows some types of light embankments. They may be divided into two categories:

- Light embankments without compensation;
- Light embankments with compensation.

The former exploits exclusively the beneficial effect generated by the lesser specific weight of the material, which translates into lesser load distributed on the underlying soft soil. The latter substitutes part of the soil that has poor foundation carrying capacity so as to improve mechanical characteristics and compensate partially or completely for the overload caused by the new embankment.

The main problem involved in the use of this technology consists in the tamping of the expanded clay: to achieve good results it is necessary to insert in the embankment itself layers of mixed stabilized granulates together with geo-synthetic strata which act as separation elements, to avoid mixing of the expanded clay and the other mixed strata.

As regards construction, the first phase consists in excavation from ground level to foundation level, at which point the geo-textile product is spread on the appropriately leveled excavation floor. In the case in point, the geo-textile material serves to distribute load but above all to avoid the phenomenon of fine material pumping, which would cause it to mix with the granular materials which make up the embankment itself. The expanded clay is laid in several layers, interposed with 200 mm thick layers of mixed granulates which make it possible to tamp the clay.

The surface layer consists of mixed stabilized granular material of thickness never less than 300 mm to prevent erosion and/or local instability.

In recent times in Italy, several works have been implemented utilizing expanded clay on toll highway A12, in the sections from Rome to Civitavecchia and Rome to Fiumicino, as well as on the Messina to Palermo highway.

In the Rome-Civitavecchia section it was decided to utilize this technology since in the twenty years life of the original embankment significant settlement phenomena had occurred leading to alterations in road surface evenness. Subsequent geological investigation revealed that degradation of the roadway was dependant on the makeup of foundation soil consisting entirely of layers of silty clay, interspersed with peat and organic silts with frequent gas pockets.

Similarly, in the Rome-Fiumicino section, when it became necessary to widen the carriageway, geological investigation showed the presence of clay soils interspersed with layers of peat. To guarantee settlement compatibility of the new structure with the existing one it was decided to utilize expanded clay to form the road embankment and foundation.

During works on the Messina-Palermo highway, potentially unstable mass was identified, with a length of some 150 m opposite and to a depth of 20÷25 m. It was decided to implement stabilization and consolidation works to minimize settlement, using expanded clay to create the embankment so as to reduce loads on the unstable mass.

Expanded Polystyrene (EPS)

Geofoam is any manufactured material created by an internal expansion process that results in a material with a texture of numerous, closed, gas-filled cells using either a fixed plant or an in situ expansion process. Geofoam materials include polymeric (plastic), glass (cellular glass) and cementitious.

Most geofoam materials are polymeric with polystyrene foams being the most common. The two types of polystyrene foam are expanded polystyrene (EPS) and extruded polystyrene (XPS). EPS and XPS are differentiated based on the manufacturing process and XPS is typically molded as thin planks or panels whereas EPS is typically molded as prismatic blocks. So the representative name for an EPS product is EPS – block geofoam.

The predominant geofoam material used successfully from a technical and cost perspective as lightweight fill in road construction is EPS. EPS-block geofoam has been used as lightweight fill worldwide since at least 1972, which corresponds to a road project in Norway. To date, EPS-block geofoam has been successfully used as a lightweight embankment fill material for roads ranging from Interstate highways to two-lane residential streets.

The use of lightweight fill materials including EPS geofoam for roadway embankments as an alternative to ground improvement increased during the 1990s due to four significant reasons. First, the overall time for construction is typically much shorter and less uncertain when lightweight fills are used rather than a foundation soil or ground improvement methods. The shorter construction time results form the simplicity of placing the blocks and the ability to place the blocks in adverse conditions. Second, lightweight fills produce relatively small undrained (initial) and consolidation settlements whereas traditional ground improvement methodologies, such as preloading, typically produce relatively large undrained and consolidation settlements. While these settlements may not affect the final road, they can negatively affect adjacent property, roads, bridges, buildings, utilities, etc.. Third, lightweight fills decrease maintenance costs because of less settlement. Fourth, the durability of EPS-block geofoam has been proven by projects completed in the 1970s.

Benefits of utilizing an EPS-block geofoam embankments also include:

- Possible elimination of the need for preloading, surcharging, and staged construction;
- Alleviation of the need to acquire additional right of way to construct flatter slopes because of the low density of EPS-block and/or the use of a vertical embankment because of the block shape of EPS;

- Use over existing utilities which reduces or eliminates utility relocation.

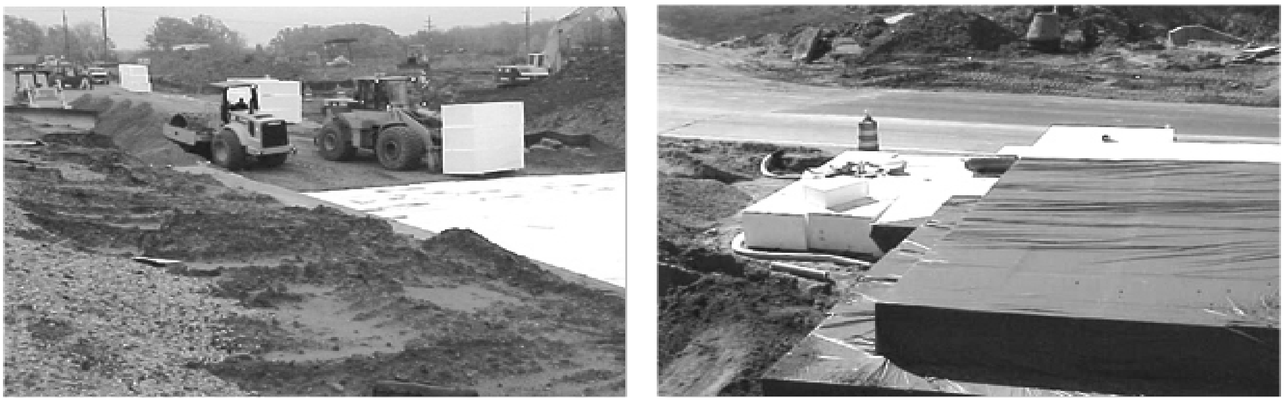

Figure 6: EPS – block geofoam application [www.falconfoam.com]

EPS-block geofoam is unique as a lightweight fill material, with a density that is only about 1 percent of the density of traditional earth fill materials yet sufficiently strong to support motor vehicles, trains and airplanes. The extraordinarily low density of EPS-block geofoam results in significantly reduced gravity stresses on underlying soil foundations as well as reduced inertial during seismic shaking.

An increase in use of lightweight fill materials for road construction is reflected in the fact that they have been emphasized by various governmental transportation agencies. The U.S. Federal Highway Administration (FHWA) has developed Demonstration Project 116, Ground improvement Methods, to enhance the acceptance and implementation of ground improvement methods by the transportation community. Lightweight fills have been incorporated in this FHWA project as a method of ground improvement by reducing the applied load [Elias V., Welsh J., Warren J., Lukas R. (1999)]. The Permanent International Association of Road Congresses (PIARC) has issued a document describing the use of various lightweight fill materials for different applications in road construction [PIARC(1997)].

It is possible to manufacture EPS blocks within a range of densities through controlling it during the first stage of manufacturing (the pre-expansion process). The overall range in EPS density possible is between approximately 10 to 100 kg/m^3 although for practical purposes the range available for lightweight fill applications is much smaller, of the order of 16 to 32 kg/m^3.

In general EPS – block geofoam has proven to be a very robust geo-synthetic product. EPS is inherently non-biodegradable and will not dissolve or deteriorate. It will not interact in any way with the ground or groundwater and will not leach any chemical into the ground or groundwater.

The EPS will lose some of its thermal efficiency which is irrelevant per se to most lightweight fill applications.

The stress –strain behavior of EPS-block geofoam is both linear and elastic up to a compressive strain of 1 percent.

Different studies have demonstrated that the compressive behavior of block – molded EPS is most dependent on density and have found a linear empirical relationship between EPS density and the Initial tangent Young's modulus E_{ti}:

$$E_{ti} = 450\rho - 3000$$

where:

ρ = EPS density in kg/m^3.

The following findings regarding the Poisson's ratio, ν, of EPS block are provided:

- within the elastic range, ν is relatively small (of the order of 0.1) and often taken to be zero for practical design purposes. However, if a more accurate estimate of ν is desired, the following empirical relationship, which indicates that ν increases slightly with increasing EPS density, can be used:

$$\nu = 0{,}0056\rho + 0{,}0024$$

  where ρ= EPS density in kg/m^3. This equation is based on research performed in Japan [Expanded Polystyrol Construction Method Development Organization, (1993)];
- beyond the elastic range ν rapidly decreases to zero. For example, testing performed on EPS with a density of 20 kg/m^3 shows, ν decreases from 0,12 within the elastic range (strains between 0 percent and 1 percent) to 0,03 at a strain of 5%.

EPS is very simple to lay since a regular-size EPS block, measuring for example 0.5 × 1 × 3 m with a density of 20 kg/m^3, weighs 30 kg and may be handled at the worksite by one person; moreover it is highly adaptable to the shapes the terrain requires.

As regards laying, similarly to traditional embankment projects, firstly vegetation soil is removed and replaced with draining material (moisture drainage) and on this the EPS blocks are placed. The blocks are staggered and laid with non-continuous joints, each layer is compacted, and soil cover along the road perimeter must be no less than 25 cm. The block layers are fixed together using a metal anchoring device with anti-corrosion protection. The last layer of EPS blocks is protected from the risk of oil and solvent infiltration by means of polyethylene or PVC film. Subsequently, a layer of cement conglomerate is spread to make the structure rigid. And finally the layers of mixed bitumen, binder and surface course are laid [NCHRP (2004 a); NCHRP (2004 b)].

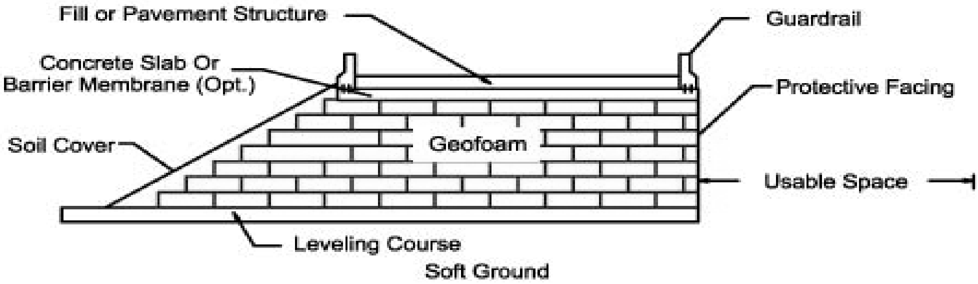

Figure 7: EPS – block geofoam embankment cross section [www.geofoam.syr.edu].

LIGHTWEIGHT HIGHWAY EMBANKMENTS TO SOLVE THE "UNDERGROUND DAM EFFECT"

Alternative, low-density materials such as expanded clay or expanded polystyrene are at the present time used to obtain lightweight embankments on foundation layers with unsuitable characteristics which it has not been possible to circumvent when choosing the route in the definitive planning stage.

In this study an attempt is made to show how these materials may also offer a viable solution where the presence of an embankment made of traditional materials has altered the underground hydrology of the territory in which the infrastructure is set.

The model employed is the same as that shown in Figure 1, the only modification made being that of the material used for embankment fill: soil type A1 has been replaced with EPS blocks in one case and with expanded clay in the other. The subsequent figure shows model discretization.

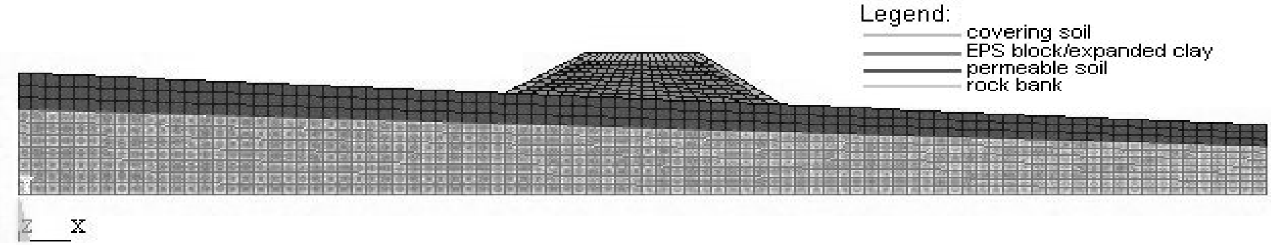

Figure 8: Model discretization using alternative materials

The analysis method is the same as that used in studying modification of the groundwaters induced by embankments created using natural soils, as reported in preceding paragraphs.

The author examined applications with EPS or expanded clay only in embankments resting on low permeability foundation soil such as type B soil, with mechanical characteristics shown in Table 2. Indeed, in the case of high permeability soil (type A) the problem of the underground dam effect does not occur, even with embankments of significant height (y = 16m).

First, the behavior of the groundwater was studied following construction of a 4 m high embankment constructed with EPS blocks, assuming the groundwater flows on a rocky layer -1.8 m below ground surface. In practical terms, this meant repeating the extreme conditions leading to groundwater flooding following overload caused by an embankment of the same height constructed using natural materials.

Table 4 shows the mechanical characteristics of the EPS block employed in the study.

Table 4: Mechanical characteristics of the EPS block used

MATERIAL	DENSITY (kg/m^3)	INITIAL YOUNG'S MODULUS Eti (MPa)	POISSON'S RATIO
EPS	20	5	0.1144

Figure 9 shows the distribution of vertical stress and the trend of the groundwater level.

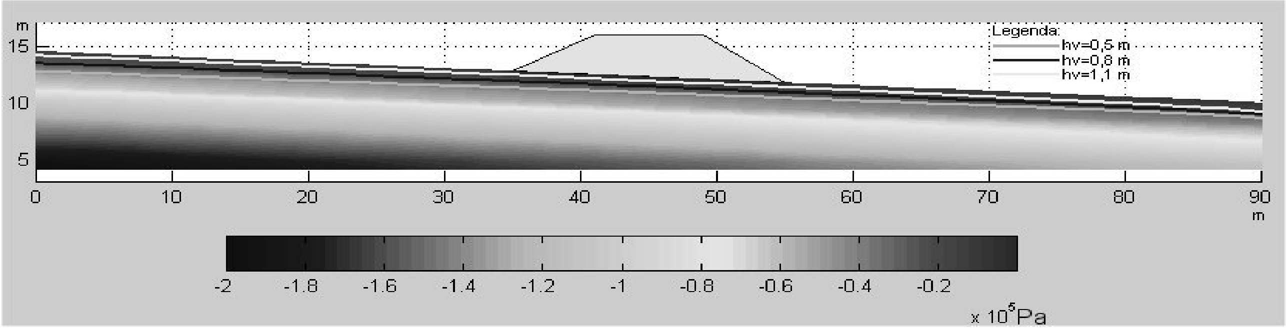

Figure 9: Vertical stress and groundwater level trends in an embankment constructed in EPS blocks

As shown in the graph, the distribution of vertical stress on the soil supporting the embankment does not seem to be influenced by overload due to the presence of the embankment itself. Consequently, soil permeability is not modified, the groundwater does not rise and neither does it flood the surface. This is true both for a water table with a downstream height of 0.5 m from the flow plane (a situation similar to that shown in Figure 4) and for water tables closer to the surface with h_v=0.8 m or h_v=1.1 m.

So in this case, the use of EPS blocks would appear decisive in preventing modifications in the local underground hydrological balance due to the embankment.

The same analysis was performed using expanded clay as embankment fill (its characteristics are shown in Table 3), under the same conditions as in the preceding example.

Results obtained are summarized in Figure 10 hereunder.

The distribution of vertical stress shows an increase at the site of the embankment and this leads to variation in foundation soil permeability and a consequent rise in groundwater level. In this case, the limit situation, that is groundwater flooding, occurs when the groundwater level has a downstream height of 0.8 m thus closer to the surface than that considered with the embankment constructed using natural soil, all other conditions being equal.

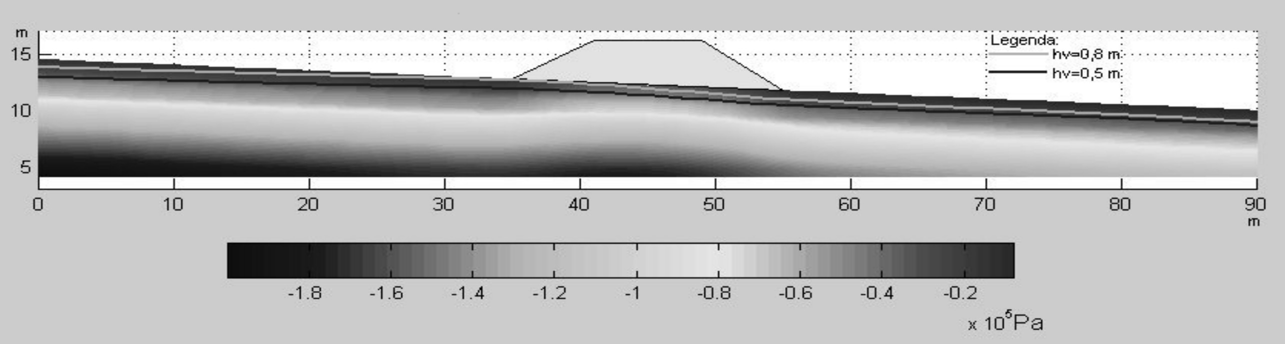

Figure 10: Vertical stress and groundwater level trends for an embankment constructed using expanded clay

Again, the author decided to study the behavior of a water table lying on a flow plane located at a depth of -1.80 m following construction of a 16 m high embankment using EPS blocks.

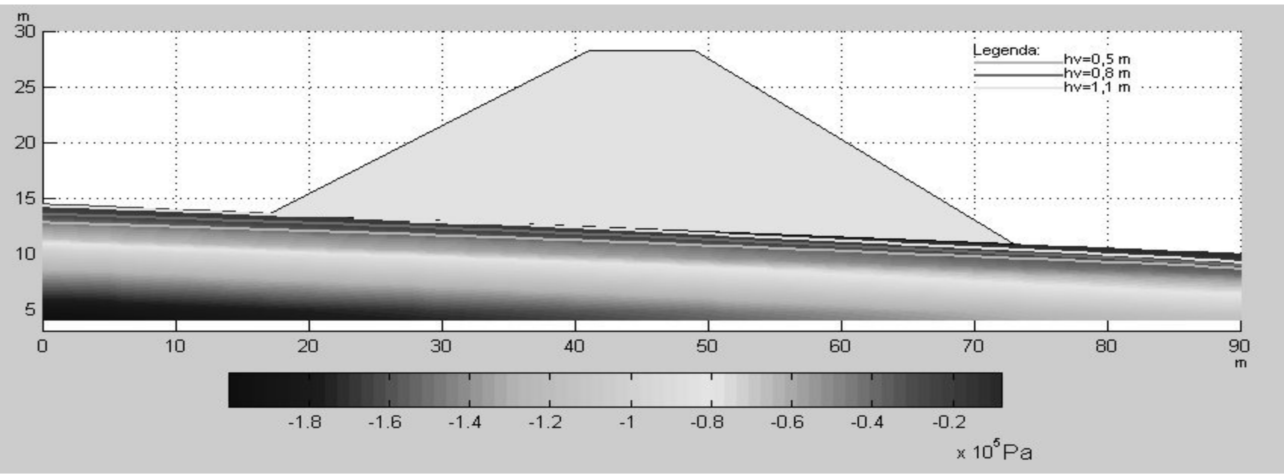

Figure 11: Vertical stress and groundwater level trends for a 16 m high embankment built using EPS blocks

In this case too, as shown in Figure 11, notwithstanding the significant size of the embankment, the low density of the EPS blocks ensured that there were no increases in foundation soil stress and consequently the trend of the underground table level remained almost unchanged also as regards water tables close to the surface (hv=1.1 m).

CONCLUSION

This work followed the methods used in previous studies to analyze the effects caused by the construction of a road embankment on the distribution of stress on foundation soil, permeability and hence the groundwater level trend.

This method makes it possible to assess from the definitive project stage effects induced by any infrastructure on a pre-existing hydrological system once the physical and geometrical characteristics of the soil, groundwater and road embankment are known.

This study highlights the fact that initial soil permeability conditions the phenomenon to a large degree. Indeed, in the case of more permeable soils, the rise of groundwater levels is slight even in the presence of apparently critical conditions such as surface water tables and embankments of considerable height. This rise is not such as to affect the road project and the bell curve is reassuring as to surrounding hydrological balance.

In the case of less permeable soil types, the situation is certainly more critical since the rise of the water table is much more substantial and leads to surface flooding also with 4 m embankments and deep water tables. This phenomenon has a negative effect on the stability of the works and at the same time causes flooding of the areas at the foot of the embankment upstream of the project.

The latter situation was analyzed by considering embankments built using low-density alternative materials: expanded polystyrene (EPS) and expanded clay.

It was found that the use of EPS blocks provided relatively satisfactory results: this material with a density of about 1% of natural soil, does not seem to cause variation in the stress status of the embankment foundation, nor in its permeability and hence in the behavior of the groundwater. This is true not only for embankments only 4 m high but also for considerably higher ones (y=16 m).

The results obtained using expanded clay do not seem to be equally satisfactory because of the greater density of this material (600 kg/m^3) which clearly generates an increase in the stress exerted on the foundation soil and thus modification of the behavior of the groundwater. However, it can be said that the rising of the table towards the surface appears less significant than that produced by an embankment of the same size constructed using natural soil, and a critical situation, identified with surface flooding, occurs only when the water table is closer to the surface.

It would therefore seem that the use of alternative materials is promising in resolving problems associated with the insertion of a road infrastructure in a given environmental context, and more specifically it can ensure that after termination of construction, it is possible to return to the preceding hydro-geological context.

Now follows the need to examine the problem of cost. At the present time, these alternative materials are very expensive above all in comparison with natural materials: costs range from 2 Euro/KN for tire fragments to 6.5 Euro/KN for fly ash and again 22÷30 Euro/m^3 for expanded clay and expanded polystyrene.

However, in analyzing costs, other aspects related to the use of these materials must be considered. In fact any cost/benefit analysis needs to address possible savings in terms of time savings for construction, reclamation of foundation soil, transport of fill and subsequent maintenance works. Again, the availability of traditional material and the accessibility of borrow pit, and consequental environmental impact should be considered.

So at this point, the problem becomes one of environmental policy: hitherto, at the international level, the research community has seen no measure on the limitation of soil consumption. Attention has always been focused on the atmosphere and surface and groundwater and there has been the establishment of limitations in pollutant emissions only as regards the latter environmental components. What is needed now is equally detailed evaluation and assessment as regards the soil, seen as a resource which again is non-renewable and should thus be protected and safeguarded, setting limitations to its use and offering incentives for the use and re-use of alternative materials.

REFERENCES

ANNUNZIATA F., CONI M., MALTINTI F., PINNA F., PORTAS S., (2004), *Progettazione stradale integrata*, Zanichelli, Bologna.

ANSYS User's Manual (1992), Revision 5.0

BIASUZZI K., MARINELLI M., VIGNALI, V. (2004) “I materiali leggeri nelle costruzioni stradali: la situazione in Italia”, Strade e Autostrade, n°5

CITRINI D., NOSEDA G., (1982), *Idraulica*, Abrosiana Editore, Milano

CONI M., MALTINTI F., SABA A., PORTAS, ANNUNZIATA F., (1998), “Analisi numerica sulle modificazioni idrogeologiche conseguenti alla realizz S.azione del corpo stradale” *Atti convegno SIIV*, Milano, pp. 295-297.

ELIAS V., WELSH J., WARREN J., LUKAS R. (1999), “Ground Improvement Technical Summaries“, FHWA – SA – 98 – 086, vol. 2, U.S. Department of Transportation Federal Highway Administration, Washington D.C.

EXPANDED POLYSTYROL CONSTRUCTION METHOD DEVELOPMENT ORGANIZATION, (1993) “EPS”, Tokyo Japan.

LAMBE T.W., WHITMAN R.V.(1997), “*Meccanica dei terreni*”, Dario Flaccovio Editore, Palermo

LO PRISCO, LUISI (2001), "Le argille espanse nella costruzione dei rilevati stradali", *Strade & Autostrade*, ed. n°3.

MALTINTI F.(2002), *La progettazione delle infrastrutture di trasporto nell’obiettivo della salvaguardia degli equilibri naturali*, tesi di Dottorato di Ricerca in Ingegneria del Territorio, XIV Ciclo

NCHRP web Document (Project 24-11), (2004 a), “Geofoam applications in the design and construction of highway embankments”.

NCHRP Report 529 (2004 b),”Guideline and recommended standard for geofoam applications in highway embankments” Transportation Research Board

PIARC – World Road Association (1997), “Materiaux legers pour remblais/lightweight filling materials”, Document n°12.02B, La Defence, France.

SMITH G. N., SMITH I.G. N (1998), *Elements of Soil Mechanics*, Blackwell Science.

www.geofoam.syr.edu

www.falconfoam.com