the Pneusol

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SUMMARY

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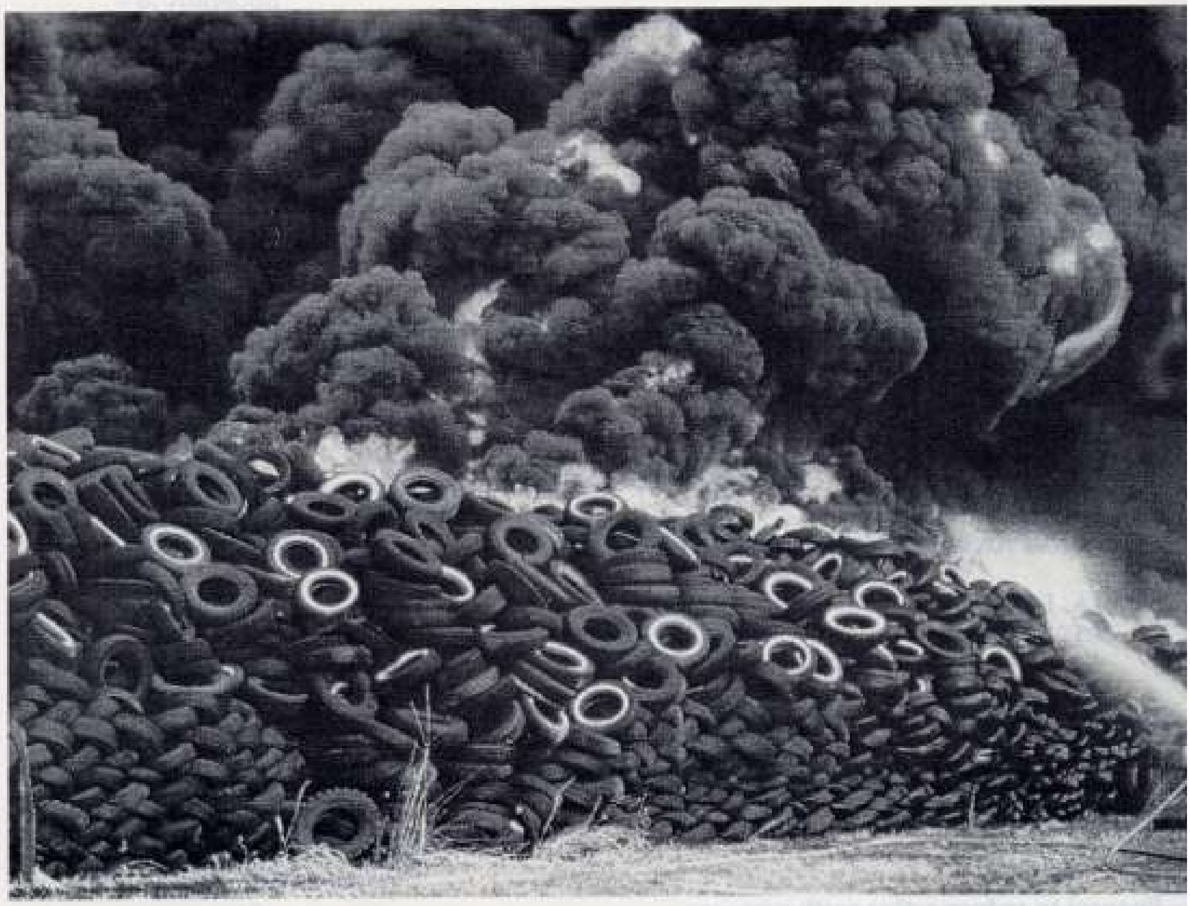

What will happen if you don't use Pneusol!

PRESENTATION

J.F. Coste, Director,
Laboratoire Central des Ponts et Chaussées

Old tyres constitute a waste material that has excellent mechanical properties and is available in quantity in all parts of our country.

In France, more than 450,000 tons of tyres are thrown away every year. Only one hundred and fifty to two hundred thousand tons are recycled in one form or another (retreads, incineration, farm use, rubber powder, etc).

The problem is not specific to France. It affects all of Western Europe (and more generally all developed countries), and some of our neighbours (Germany, Italy and Great Britain) even more acutely than ourselves, since they have roughly comparable populations (and thus comparable numbers of motor vehicles) but only about half as much land area. The European "deposit" of old tyres is about five times as large as the French one.

While old tyres do not contribute directly to pollution (unless they are burned in the open air), they affect our environment in the long term because they are not biodegradable.

The first research in France on the use of old tyres to reinforce soils was done in 1976, and led in 1978 to the submission of a report to the Délégation Générale à la Recherche Scientifique et Technique.

Generally speaking, Pneusol (registered trade mark), a combination of tyres and soils, not only helps to consume stocks of old tyres, but also improves the mechanical properties of soils.

Today more than 60 structures have been built in France and 12 in Algeria covering a wide range of civil engineering applications mainly in order to reinforce earth structures, at lower cost than with conventional technologies. Other trials, aimed at other applications, are in progress. The Strasbourg Regional Public Works Laboratory, for example, has been conducting field tests of Pneusol as an vibration damping and noise abatement material.

The present document, which groups English version of articles already published on the subject , is intended to give project supervisors and contractors technical and cost information about a material that has the characteristic of being of benefit both to roads and to the environment, and that can be expected to be very competitive in economic terms.

PNEUSOL TYRESOIL TIRESOIL

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Colloque "ROUTES ET DEVELOPPEMENT" - E.N.P.C., PARIS (Mai 1984)

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SYNOPSIS

Pneusol Tyresoil, a combination of soil and tyre parts (either tied together in chains or placed in layers), has been studied. Its good performance was found suitable for the construction of a retaining wall 5 m high and 10 m long. Other structures are now being tested (roads over karstic zones, impact protection works, etc ...).

INTRODUCTION

Engineers and researchers have a keen interest in ways of reinforcing soils by inclusions possessing tensile strength, and in developing civil engineering materials that are more inexpensive but otherwise comparable with existing materials.

These two apparently contradictory aims can now be reconciled by a new material, Pneusol Tyresoil, a combination of soil and parts of old tyres (which may be tied together in chains or placed in tiers).

A survey conducted in 1973 by the Omnium Technique d'Aménagement (OTAM) in twelve large French cities revealed that old tyres account for the bulk of synthetic and natural rubber wastes (about 450,000 tons a year, growing at 6.8% year), but this does not hold in the developing countries, where they are reused in a great variety of ways. Even so, when compared to imported steel, it is a very economical reinforcing material - provided that its mechanical properties are competitive. This is what we have attempted to determine in this study.

1 - GENERAL

1.1. - general remarks ant the behaviour of Pneusol Tyresoil

The word "soil" covers both the whole range of natural ground, with mechanical properties as varied as those of powdery and cohesive materials, and a variety of wastes.

The word "tyre" covers all parts of an old tyre (two sidewalls and a tread), used together in chains or in tiers and capable of withstanding large tensile forces.

No special grading is required of the soil reinforced with tyres, since the tyre-soil interaction does not depend primarily on friction, as it does in geotextile-reinforced structures and reinforced earth.

Pneusol Tyresoil has the advantage of making it possible to improve the mechanical properties of the soil either anisotropically, i.e., only in the directions in which the material is most highly stressed (layers, linear strips, etc ...), or isotropically, in all directions (continuously linked elements mixed with fill).

1.2. Behaviour

The main components of a tyre are :

- the beads, consisting of rubber-covered metal wires or braids that do not stretch and so hold the tyre securely on the rim, round which the plies of the carcass are wrapped;

- the carcass, an assembly of plies made of spun or braided cords of natural fibres (cotton), synthetic fibres (nylon, rayon), or metal; these cord plies constitute a sort of reinforcement of the tyre, on which the sidewalls and tread are applied;

- the sidewalls and tread, made of one or more rubber-based mixtures to which carbon black is added.

Currently, most of the tyres produced in the world have carcasses made of braided rayon cords; these are very strong : a cord only a few tenths of a millimetre in diameter (0.6 to 0.8 mm) may have a tensile strengh of 400 N.

As we have seen, the various parts of a tyre are very strongly reinforced. It has been rather difficult to analyze them in the laboratory. However, we can attempt to determine their range of behaviour, especially in the simple case in which the functioning of Pneusol Tyresoil depends primarily on friction (flattened treads, for example). But this does not reflect the commonest case, in which whole treads are used on edge.

Many tests carried out on cylindrical specimens of Fontainebleau sand reinforced by discs of aluminium foil (1) or latex have demonstrated the existence of considerable cohesion in the former case. This cohesion is proportional to reinforcement density R_T where R_T is the tensile strength of the aluminium foil and D_h is the spacing between the discs (fig. 1).

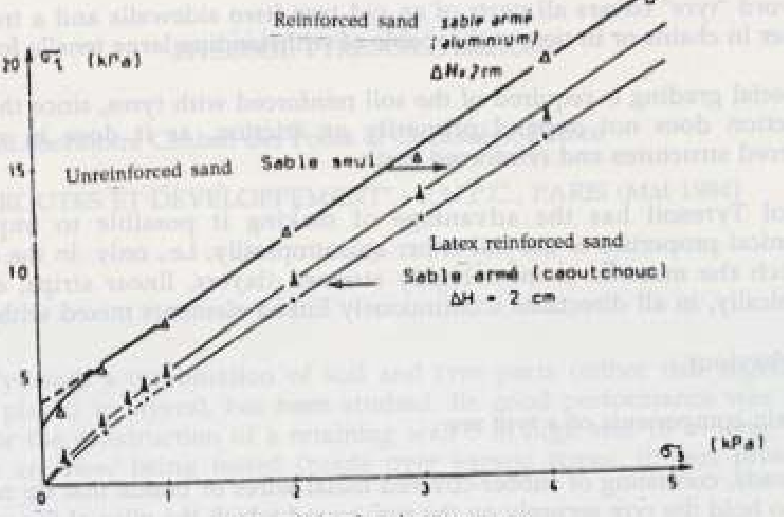


Fig. n° 1 : Intrinsec curves

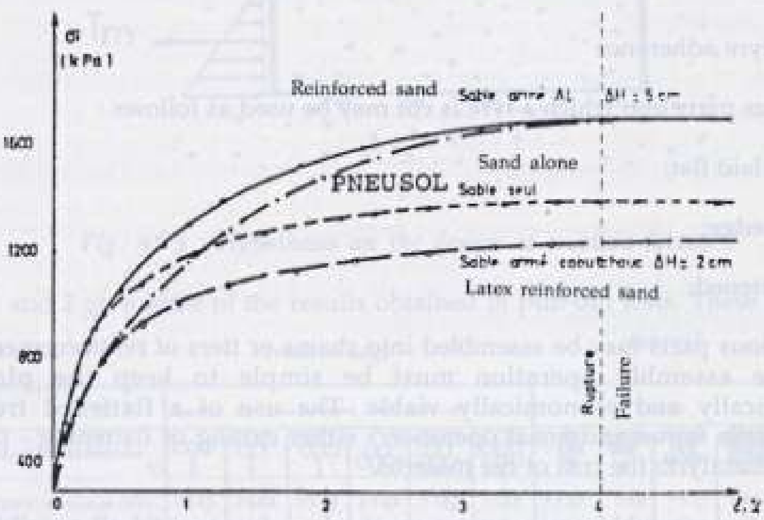
The latex-reinforced sand, in addition to exhibiting no cohesion, even has a slightly smaller angle of internal friction .

It may therefore be assumed, on the basis of these simple tests, that the Mohr's envelope of Pneusol Tyresoil lies between that of a steel-reinforced sand and a sand reinforced with rubber, which is a mixture of latex and various chemicals, with a large induced cohesion because of the excellent mechanical properties of the steel. It is certain that the failure of such a composite material results primarily from the failure of the sand.

Figure 2 shows the stress-strain curves of the same materials. The modulus of sand-latex is invariably smaller than that of sand. In view of the results already mentioned, if the appropriate quantity of tyres is chosen to be incorporated in the soil, it is possible to obtain a composite material having a low initial modulus and a high deviator stress at failure.

Such a material has many possible applications, first of all in retaining structures, by making use of the high ultimate strength and by controlling deformation; in avalanches protection works; in protecting works on bridge piers, and so on.

The behaviour of Pneusol Tyresoil is in fact highly complex and, depending on the way the tyre parts are used, the effect of soil-tyre friction may be far smaller than the anchoring effect, which cannot be investigated in the laboratory.



(Pneusol curve is an hypothesis)

Fig. n° 2 : Strain stress curves

2 - TECHNOLOGY

2.1 - Mechanical properties of tyres

To make it possible to compact the fill properly, the tyre is cut into three p arts, two sidewalls and one tread, to make the most of the beads and the reinforced plies. There exists a machine capable of doing this cutting work - the RTM 80, which has been in continuous use in Germany since February 1980. However, this cutting may not be absolutely necessary when this material is used as an energy absorber. Indeed, the void left by the air chamber space gives the material as a whole a very low modulus, and high deformability is desirable in structures of this type.

Mechanical tests have been carried out using a press fitted with a device that records tensile force versus strain. All makes of tyre habe been tested. A statistical study of passenger-car tyres has been conducted. The following results were obtained :

- The mean tensile strength of treads is 56.0 kN, with a standard deviation of 24 kN; the probability that the tensile strength of all treads exceeds 26 kN is 90%; that it exceeds 36 kN, only 80%;

- as for sidewalls, there is practically no difference between the two sidewalls of a given tyre; sidewall strength ranges from 17 kN for the least reinforced to 52 kN for the most heavily reinforced, with a mean of 25 kN and a standard deviation of 10 kN.

2.2 - Soil-tyre adherence

The various parts into which a tyre is cut may be used as follows :

- sidewall laid flat;

- tread on edge;

- tread flattened;

These various parts may be assembled into chains or tiers of reinforcement. In all cases, the assembly operation must be simple to keep the placement technologically and economically viable. The use of a flattened tread, for example, calls for an additional operation - either cutting or flattening - that may add significantly to the cost of the material.

However, the assembly arrangement must take advantage of all possibilities of varying the strength in zones where the tensile forces are greatest.

Full-scale tensile tests of tyre parts embedded in fill have led to a good understanding of the soil-tyre interaction.

While flattened-tread/soil adherence depends primarily on the soil-rubber interaction of the tyre, this ins not the case with treads on edge or with sidewalls . For example, the tensile force applied to a tread on edge is resisted by (fig. 3) :

- soil-rubber friction on the exterior vertical surface of the tread, i.e. -, along the whole side surface, the area of which may vary with the force applied, since deformation of the tread is large;

- the passive earth pressure on the front of the tread;

- soil-soil friction along the two horizontal shear surfaces bounded by the edges of the tread.

If sidewalls are used, the first two effects may be regarded as relatively small, since the sidewall is rather thin and the soil-rubber adherence is itself small. The third effect is largely preponderant, especially since these shear surfaces increase with increasing applied force (this applies in particular to treads on edge). By contrast with all the reinforced soils in which soil-reinforcement friction is the key parameter in good performance, this direct mobilization of soil-soil friction makes it possible to use fill materials of lower quality, because tests have shown that soil-reinforcement friction is invariably smaller than internal friction.

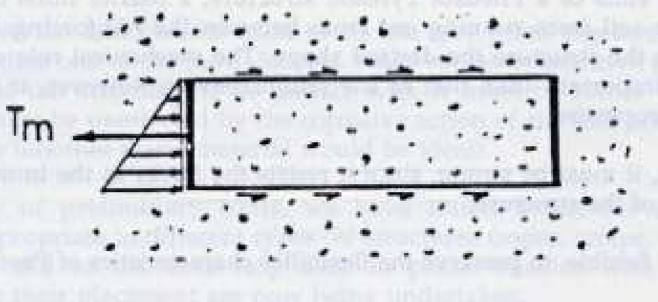


Fig. n° 3 : Hypothesis on the design of traction forces

Tables 1 and 2 give some of the results obtained in pull-out tests. These values are large .

	Tread on edge						Sidewall			
	Bande de roulement sur chant						Flanc			
Nombre d'éléments 1)										
Effort maximum(KN) 2)	>44,3	>68,0	>44,4	>40,8	>38,2	>56,0	>43,0	54,0	>57,5	>33,0
Déplacement correspondant à l'avant de l'élément (cm) 3)	> 43	>26	>24	>20	>24	>13,5	>36	46	>38,5	>25,5
Effort pourΔL=10cm (KN) 4)	26,0	45,0	21,5	26,2	21,2	49,5	18,0	25,0	22,5	20,0

	Tread flattened			Tread on edge			Sidewall		
	Bande de roulement aplatie			Bande de roulement sur chant			Flanc		
Nombre d'éléments linéaires. 1)									
Effort maximum(KN) 2)	31,0	48,0	68,0	33,5	32,0	41,0	19,5	30,0	≥33,5
Déplacement correspondant à l'avant de l'élément(cm) 3)	12	29	44	17	32	62	7	40	≥29
Effort pour ΔL= 10 cm (KN) 4)	30,0	39,0	36,0	25,0	19,0	16,0	19,0	20,0	25,0

Résultats des essais sur armatures linéaires pour une hauteur de remblai de 1 m.

Tests results on linear reinforcements under 1 meter height

1) Number of elements
2) Maximum force
3) Displacement
4) Traction for
ΔL = 10 cm

2.3 - Technological factors

a) The facing

At the free ends of a Pneusol Tyresoil structure, a barrier must be provided to prevent the soil from running out from between the reinforcing layers or rows and to give the structure the desired shape. The mechanical role of the facing is much less important than that of the reinforcement; however, it must have the following properties :

- first of all, it must be strong, since it resists the forces in the immediate vicinity of the end of the structure;

- it must be flexible, to preserve the flexibility characteristics of Pneusol Tyresoil;

- then, it must be attractive, because the appearance of the structure depends on it;

- finally, it must be made up of elements that can be mass-produced and that make construction simple and rapid (fig. 4) .

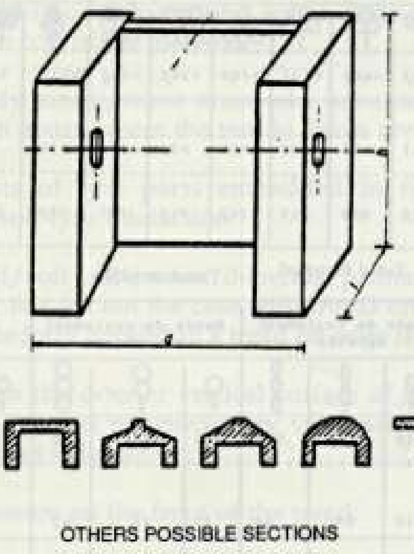


Fig. n° 4 : Facing elements

There are already many prefabricated retaining walls on the market; they can be used as facings on Pneusol Tyresoil structures with only a few modifications. The individual elements are placed in horizontal rows, and the row just above is staggered, making it possible to plant greenery and flowers in the spaces between rows.

b) Attachments

The problem of the attachments used to tie the tyre parts together and to the facing is doubtless one of the most delicate. Since rubber is sensitive to punching, the surfaces of the attachments in contact with it must be rather broad. Like rubber, they must be unaffected by the corrosive action of the soil, and they must be inexpansive (another waste material would be ideal).

In the course of preliminary trials, we have tested a number of types of attachment appropriate to different types of structures (ropes, straps, metal parts, metal hooks, and so on) and very easy to place. Studies with a view to industrializing their placement are now being undertaken.

3 - INTERNAL DESIGN OF PNEUSOL TYRESOIL

The design of the Pneusol Tyresoil depends on the mode in which it functions.

There are two main cases :

- anisotropic (retaining walls, foundation rafts, etc ...);

- isotropic (protection of bridge piers, artificial islands).

3.1 - Anisotropic case

The aim here is to reinforce the soil in the directions of greatest stress. We cannot review all possible design methods, but merely show through a few examples that our design resources habe been adequate for the first few structures.

a) Retaining walls

The design principle used in determining the tensions in the reinforcement of a retaining wall is to write the equations of local equilibrium between the facing and the tier of reinforcements at the level in question (fig. 5). It is assumed that the earth between the reinforcments is at the limit state and that the principal stresses are parallel and perpendicular to the facing.

The advantage of this design method is that it makes it easy to calculate the tensile force in each tier of reinforcements.

The assumption that the earth between the reinforcements is everywhere at the limit state is valid because the strain of the tyre reinforcments is sufficient to mobilize all the shear stregth of the soil.

This method also assumes that the tensile forces in the tiers of reinforcement are greatest at the facing.

The local equilibrium between the facing and the tier of reinforcements is expressed by the equation

$$T = k_a \ \sigma_v \ \Delta H$$

where ka is the coefficient of active pressure $\tan^2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)$ in the case of a powdery soil and ΔH is the spacing between two tiers of reinforcements.

The final calculation of tensile force T requires an assumption concerning the distribution of vertical stress σ_v. The equilibrium of the wall under the effect of the active earth pressures exerted on it is such that three types of distribution may be considered : uniform, linear, and Meyerhof's (fig. 5).

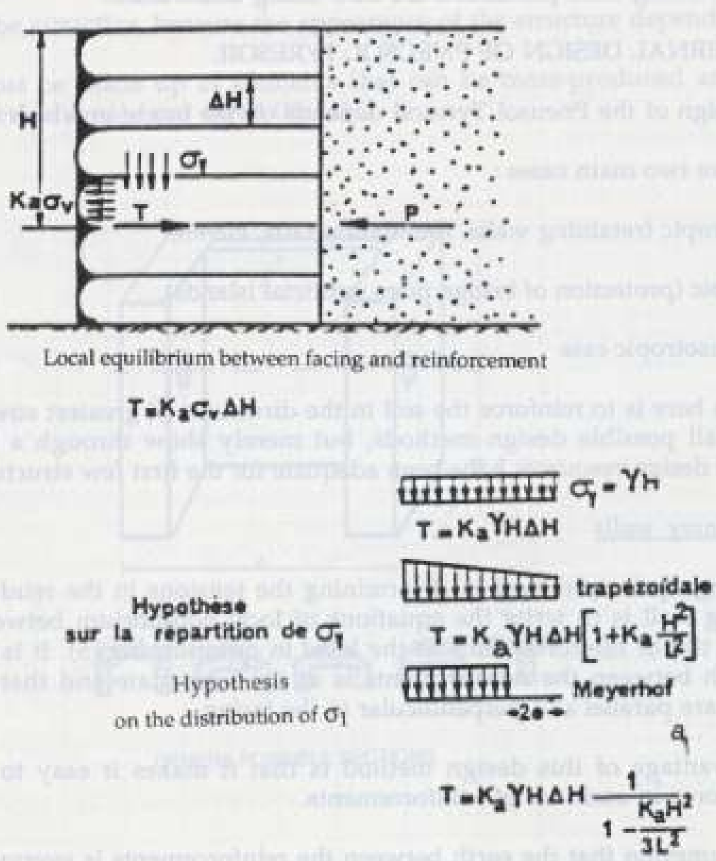


Fig. n° 5 : Internal design of Pneusol wall

As for the determination of the lengths of the tyre elements, soil-tyre adherence tests have shown that, with combinations of more than three elements, there is practically no further possibility of slippage under the effect of the applied forces.

b) Reinforcement of embankments

The method used is the method of sections. The surface of failure, treated as a cylinder having a circular base, is subdivided into vertical sections such that in each section there is only one reinforcement intersecting the surface of failure.

In the calculation of the equilibrium of a section, it is assumed that the tensile force mobilized is oriented in the direction of the reinforcement. Failure may occur either by loss of adherence, i.e. slippage of the reinforcement, or by the breaking of the reinforcement, assumed to occur at the surface of failure.

Tests have shown the first type of failure (failure of adherence) occurs only when isolated tyre elements are used. Such cases are very rare. Generally, the tying together of several elements gives the resulting reinforcement a good anchorage.

Study of the equilibrium of the zone at the limit state makes it possible to determine an overall factor of safety in accordance with the usual methods of the theory of slope stability.

3. 2 - "Isotropic material"

In this case, a continuous linear chain of tyre parts (or possibly of whole tyres) is incorporated in the soil in a three-dimensional pattern so as to reinforce the soil in all directions (mixing of soil and chain).

The soil particles are doubly imprisoned, first inside the tyre parts (e.g., treads), then inside the loops of the unbroken chain. They are therefore strongly bound together by this double roll effect, by confinement that introduces a substantial dilatancy effect, then by soil-tyre friction and the internal friction of the soil itself.

These effects give this form of Tyresoil a very large "isotropic" cohesion. A great variety of soils may be used : concret rubble, various solid wastes, stones, gravel-sand, etc ... The cohesion may be calculated in many simple ways. We shall mention one of them :

Let us imagine that we can carry out a biaxial test of the Pneusol.

The method then consists of writing the equations of local equilibrium of a portion of soil having dimensions dx, dy, located near the membrane of the specimen, among all the forces applied to it (fig. 6).

We add the further condition that there is no slippage between the soil and the continuous chain (perfect adherence).

Let n be the number of times this chain reaches the surface dx, dy, and E be its modulus.

Study of the equilibrium of the zone at the limit state makes it possible to determine an overall factor of safety in accordance with the usual methods of the theory of slope stability

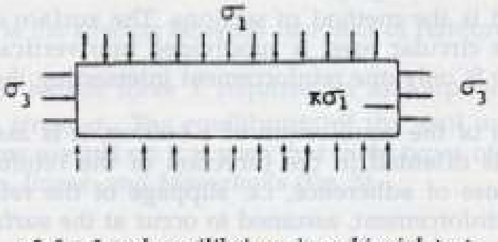


Fig. n° 6 : Local equilibrium in a biaxial test

When a deviator $\sigma_1 - \sigma_3$ is applied to the specimen, there is automatically a slippage of the grains with respect to one another, a slippage that results in :

- a vertical strain ε_1 and a horizontal strain ε_3 of the specimen,

- tensioning of the chain.

The horizontal strain is closely related to the modulus E, insofar as the assumption of perfect grain-chain adherence imposes the same strain of the soil as of the chain.

Let us further suppose that stresses σ_1 and K σ_1 (K being a coefficient characterizing the state of the medium) are principal stresses, i.e. vertical and horizontal.

The strain of the chain will then be :

$$\varepsilon_3 = \frac{(K\sigma_1 - \sigma_3)\, dx\, dy}{E.n}$$

$$\varepsilon_{chain} \times E \times n = (K\sigma_1 - \sigma_3)\, dxdy$$

$$\varepsilon_{chain} \times E = R'_t, \text{ the tensile strength of the chain}$$

$$R'_t \times n = (K\,\sigma_1 - \sigma_3)\, dxdy$$

$$\text{Now, } n = \mu \frac{\gamma}{\gamma_t} \cdot \frac{dxdy}{(1 + \mu \frac{\gamma}{\gamma_t})\ s}$$

where

γ is the density of the soil

γ_t is the density of the chain

s is the cross-sectional area of the chain

μ is the percentage of mixing

$$\sigma_1 = \frac{1}{K} \sigma_3 + \mu \frac{\gamma}{\gamma_t} \quad \frac{R'_t}{(1 + \mu \frac{\gamma}{\gamma_t})\ s}$$

The incorporation of a reinforcement results in a large increase in lateral stress 3, the value of which is

$$\Delta\sigma_3 = \mu \frac{\gamma}{\gamma_t} \quad \frac{R'_t}{(1 + \mu \frac{\gamma}{\gamma_t})\ s}$$

This equation is general, since it specifies neither the state of the soil nor that of the chain, and the soil and chain may reach the limit state independently.

When both components are at the limit state

$$\sigma_1 = \frac{1}{K_a} \quad \sigma_3 + \Delta\sigma_3 = K_p \ (\sigma_3 + \Delta\sigma_3)$$

$$\tau = \sigma \tan \varphi + \mu \frac{\gamma}{\gamma_t} \frac{R_t}{(1+\mu \frac{\gamma}{\gamma_t})\, s} \frac{\sqrt{K_p}}{2}$$

The Pneusol therefore behaves like a soil having cohesion.

Structures built of isotropic Pneusol must be rather massive for this schematic representation to be valid.

4 - AREAS OF USE

One of the qualities of Pneusol is its flexibility, which enables it to withstand large differential settlments. The use of tyres arranged in tiers also gives a better distribution of forces in the reinforced soil mass and on the foundations.

This essential quality makes Pneusol Tyresoil a very good civil engineering material, which has the following advantages :

- standardization and speed of execution;
- construction in stages and sections;
- the possibility of using a mediocre fill;
- the possibility of building :
  . curved walls having a short radius of curvatures;
  . structures on land or in water;
  . structures with architectural effects that enhance the site;
- Improvement of the environment through the comsumption of an abundant and cumbersome waste;
- energy savings through the substitution of a waste material for steel;
- improved compaction.

There are many possible applications :

a) Multi-layer structures

These include, for example, retaining walls, small abutments for metal bridges, dykes, and reservoirs for fire-fighting water. The use of Pneusol, with or without a facing, makes it possible to save space by making the embankment slope steeper. The flexibility of the material means that it can be used tu support roads on compressible ground.

An experimental wall 5 m high and 10 m long, built at Nancy in 1982, has demonstrated how easy it is to place multi-layer Pneusol structures (fig. 7). The facing elements are placed with a slight rake to take out the deformations of the tyre reinforcements. This wall was built by the Nancy Regional Laboratory and has been followed up by Messrs. Delmas and Matichard (with the financial assistance of the ANRED).

b) Single-layer structures

For single-layer and other structures, we put forth a few ideas concerning possible uses. Pneusol might be used to make it possible to build tracks using non-coherent materials of low stability, on karstic and compressible ground.

During compaction, the treads, used together in a tier, expand under the action of the compactor. After compaction, they contract and so confine the fill materials. It is as if the fill is highly prestressed to increase the bearing capacity of the Pneusol Tyresoil structures.

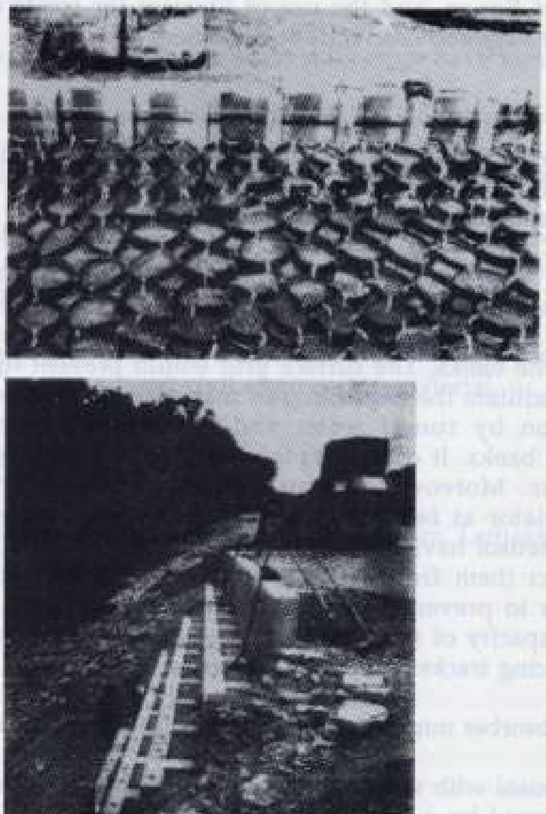


Fig. n° 7 : Experimental Pneusol wall

The use of Pneusol may make it possible :

- to increase the mechanical strength of fill by introducing cohesion;

- to limit the thickness of fill required;

- to prevent, in part, mixing of the various layers of the foundation.

Trucks and other construction equipment impose large stresses on the ground. Some tracks are unpaved either because they are temporary (site roads) or for economic or even ecological reasons (forest roads).

The use of Pneusol (possibly in conjunction with a low-strength, nonwoven, geotextile, either on the foundation soil itself or on a thin subgrade, can provide sufficient stability for such tracks.

A Pneusol track is now being tested with the help of the Centre d'Etudes Routières (C.E.R.) of Rouen, and the use of Pneusol for roads on karstic zones with the Laboratoire Régional des Ponts et Chaussées of Nancy.

c) Other structures

It is sometimes difficult to ensure the stability of structures built in water, because the soil must be held in place without disturbing the flow of water along the embankment, since this may lead to erosion of the banks.

The use of Pneusol with a suitable fill (gravel), possibly in conjunction with a grid at the surface, would first of all make it possible to absorb current and wave energy and then to apply to the ground surface a surcharge that would serve to prevent erosion of the banks. The surface grid would prevent the washing away of the gravel and facilitate the depositing of matter in suspension. Pneusol could limit topsoil erosion by runoff water and the removal of vegetation from frequently travelled banks. It could be placed dry or in water, on the bottoms of canals and streams. Moreover, because of its mechanical properties (low modulus, high deviator at failure), it would be an excellent energy absorber. Several layers of Pneusol having different moduli could be placed atop existing structures to protect them from impacts by falling bodies and avalanches, or around bridge piers to prevent damage by impacts from boats. As proof of the energy-absorbing capacity of tyres, simply consider how they are used at tricky corners on motor racing tracks and alongside docks.

A Pneusol energy absorber might, for example, he built in three layers :

- a first layer of Pneusol with whole tyres (not cut) arranged in tiers, tied together, of course, and covered by a small thickness of fill (which might be compacted very little or not at all; the modulus of this layer would be very low because of the voids left by the inner tube spaces;

- a second layer of Pneusol made with tiers of sidewalls;

- a third layer of Pneusol made with tyre treads on edge.

There is a gradual increase of modulus from layer to layer. The arrangements made would of course depend on the amount of energy to be absorbed. Preparations for preliminary tests are now being made with the help of the C.E.R. of Rouen.

Another possible application of Pneusol would be in foundations for vibrating machines, to protect their environment by isolating them from it.

A final possible application of Pneusol is the construction of artificial islands to protect bridge piers. They could be built in place under water or on barges that would then carry them to where they were to be placed.

CONCLUSIONS

This study touches on practically all facets of the use of Pneusol Tyresoil as a civil engineering material.

Tensile tests of tyre parts and of soil-tyre adherence have yielded good results.

There are a great many potential applications. However, in the current state of our research, we have built only one experimental wall 10 m long and 5 m high. But other experimental structures are being planned or prepared.

It should be noted that, according to experts, tyres that habe been buried in the ground for more than 40 years have been recovered perfectly intact and without the slightest sign of deterioration.

The promising research results, ease of use, and excellent long-term performance make Pneusol Tyresoil a good civil engineering material.

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PNEUSOL, "TYRESOIL" AND THE STABILIZATION OF SLOPES

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SYNOPSIS

Research on the mechanism and design of Tyresoil was begun in 1978 by the Laboratoires des Ponts et Chaussées and led up to the construction of the first experimental Tyresoil wall at Langres in 1982. Since then, many other structures have been built, including retaining walls (Fertrupt) and structures to prevent avalanches or rock slides (La Grave); Tyresoil has also been used to stabilize unstable slopes (Kruth). Our paper deals with possible applications of this material, especially for the stabilization of slopes as at Kruth, where it was used in a sort of retaining wall 80 m long and 4 m high embedded in an unstable slope to support a road. Measuring instruments have been buried in the fill to monitor its behaviour (settlement, deformation, and stresses in the soil).

1 - PURPOSE AND GEOTECHNICAL CONTEXT

The stability study concerne a section of the kruth-Marstein road near the Wildenstein dam. In this zone, the slope of the natural ground is very steep (30 to 40°). The local road (CD 27) cut into the mountainside has a mixed cross-section. The slopes created range from about 40 to 60° on the uphill side and from about 40 to 45° on the downhill side. The uphill slope is undergoing backward erosion, clearly visible at the top of the slope.

The downhill slope, close to the limit equilibrium, is undergoing deformations that have resulted in cracks and subsidences in the shoulder and in the pavement. However, there has not yet been any failure.

The subsoil consists of ancient sediments, metamorphized and considerably tectonized by the formation of the Vosgian massif. During the Alpine orogenesis, at the end of the Tertiary era, various faults were reactived. Finally, in the Quaternary, a glacier of which the moraines can be seen occupied the upper valley of the Thur and heavily marked its sides.

This turbulent history of the Marstein massif explains the irregular arrangement of the rocks along the local road. These are compact greywackes forming rock spurs that have withstood erosion, alternating with highly fractured, very friable and quick folded schistous zones.

There is an altered cover more than a metre thick consisting of frost-sensitive materials.

In boreholes, we find a varying thickness of rather clayey angular gravels resting on a rocky substratum. These gravels, identified as "debris" on the cross-sections, constitute the layer of alteration of the underlying rocks. It is difficult to distinguish the debris in situ from the debris brought in as fill, since the latter was taken nearby. The longterm shear characteristics of the fraction smaller than 5 mm were determined. They are low for the general slope of the site :

$$\Phi' = 26°$$
$$C' = 0$$

The mean pressiometric characteristics of the altered layer are low :

* down to 2.5 $\quad p_l = 1.4 \times 10^5$ Pa

$\quad E < 10 \times 10^5$ Pa

* beyond - 3 m $\quad p_l = 4 \times 10^5$ Pa

$E_{mean} \quad 30 \times 10^5$ Pa

In short, the factors unfavourable to the stability of the downhill slope are :

- the rather large thickness of debris (in situ and fill);
- the poor mechanical properties of this debris, which is alterable and exposed to water circulation;
- the excessive steepness of the existing slopes;
- the steep slope of the rocky substratum or of the top of the compact debris.

2 - POSSIBLE APPROACHES TO REINFORCEMENT

In the present case, the possible solutions included a retaining wall; strengthening of the pavement limited to stabilization of the subgrade to a certain depth to prevent large differential settlement; reinforcement of the slopes; or some combination of these approaches. In the case of slope reinforcement, however, there must be some assurance that the mass of materials replacing the disturbed earth will be stable with respect to the fill and with respect to the underlying soil.

Several approaches may be considered : gabion walls; inverted tee walls; crib walls; dry stone gravity retaining walls; or gravity retaining walls of reinforced soil (Reinforced Earth, geotextiles, Pneusol, ...).

The final choice among the technically feasible solutions offering adequate practical benefits is based on the cost-benefit ratio of the structure. In the present case, the Tyresoil approach was chosen.

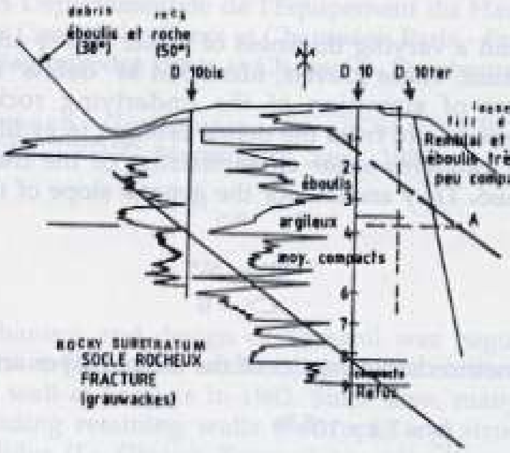

Fig. n° 1 : Penetrometer tests

3 - TYRESOIL SOLUTION

Used tyres are a blight of our civilization. There are some 450,000 tons of them in France, and getting rid of them is a knotty problem. Should they be burned? This creates pollution and becomes expensive in the long run as the tyres have to be brought in from greater and greater distances. Can they be destroyed by pyrolitic or cryogenic methods? This is even more expensive.

These wastes are rather uniformly distributed throughout the country, with a few concentrations in the vicinity of tyre manufacturing and retreading plants. The Tyresoil solution consumes only a modest number (about 3,000 tyres for a project of average size, but this of course depends on the size of the structure to be rebuilt). There are several ways of using old tyres. The technique applied on local road CD 27 is one of them.

3 - 1) Design of the structure

The Tyresoil solution is a "wall" of soil reinforced by sheets of tyre treads, on edge, about 50 cm apart, resting on the sound rocky substratum (fig. 2). All this acts as a flexible wall capable of retaining earth to a height of 5 to 6 m.

Tensile tests of treads have shown that they can withstand large forces, of the order of 50 to 75 kN (5 to 7.5 tonnes). Tests of the extraction of tyre parts embedded in embankments of different heights have shown that soil-tyre adherence is excellent.

The fill between two sheets of treads on edge is heavily reinforced, because soil-soil shear forces, rather than soil-inclusion shear forces, which are much weaker, are mobilized on both sides of the sheet.

Since the fill inside the treads exerts no active pressure, and that between two sheets is securely reinforced, Pneusol stabilizes slopes much more effectively than conventional processes (slope 1/2 or 1/3). Schematically, the structure as a whole is like a stack of small gabions separated vertically by about 30 cm of earth. All of the excavated material was reused.

Figure 3 shows the number of tyre treads on edge; they are tied together by polyester straps.

The structure is designed as a gravity wall. For overall stability, the factor of "safety" of the slip circles intersecting the reinforcing sheets has been substantially increased.

As in the case of other approaches, drainage was included.

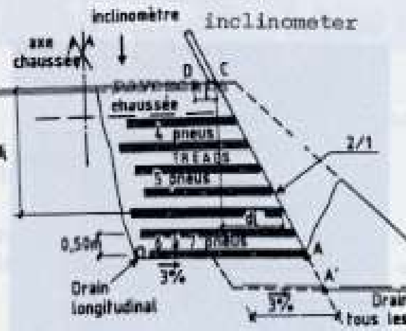

Fig. n° 2 : Profile of the structure

3 - 2) Construction of the Pneusol mass

Generally speaking, there is no fundamental difference between the construction of a Pneusol mass and that of reinforced earth or soil.

The work can be done by any civil engineering or earthwork contractor, and no special experience or knowledge of Pneusol Tyresoil is required. The contractor chosen was a small local contractor who had never built any reinforced structures.

The structure was built in sections 20 m long. Half of the local road was removed down to the rocky substratum. The material was stockpiled on the edge of the excavation. The sheets of edgewise treads were prepared in a corner of the site, as planned. They were set in place at the indicated height. The structure was filled and the materials compacted by a small compactor at regular intervals, with all the precautions inherently necessary in such cases : small thickness of fill, adequate water content, large number of passes, and so on. The basic aim of compaction in the case of a Pneusol structure is to prevent any subsequent subsidence of the material. This is the same aim as for any structure that is to support a superstructure (pavement, etc...), and so is not specific to Pneusol; all recommendations and rules of the art concerning the compaction of fill also apply to Pneusol. The reinforcements made of tyres are laid down flat and quite taut, so that there are no gaps between the different treads. Filling should be done in such a way that the treads, thick and light, move very little. Pouring from top to bottom was recommended.

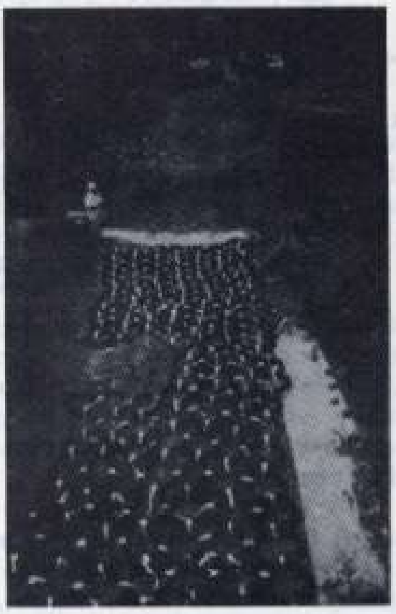

Fig. n° 3 : Disposal of sheet of treads

Fig. n° 4 : Transportation of treads

3 - 3) Findings and costs of the operation

The structure, 80 m long and from 2.5 to 4.5 m high, was completed at the end of October 1984. It has withstood two very severe winters, with temperatures of - 25° C in 1985.

Inclinometer measurements have not detected any movements behind the wall. The settlements of reference points and settlement meters are of the order of 0.5 to 1 cm at the base of the wall. The pavement is free of deformations and cracks.

The total cost of the structure, for a treated length of 80 m and a height ranging from 2.5 to 4.5 m, was 270,000 francs, broken down as follows :

- Materials : 5,500 tyres at 4 F	21,200 F
straps and clips	10,000 F
- Work (including excavation, filling, compaction, assembling the tyres into sheets, setting the sheets in place, etc)	76,000 F
- Drainage	40,500 F
- Complete pavement	122,500 F

CHARACTERISTICS AND USES OF "PNEUSOL" LIGHT GROUND FILL

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SYNOPSIS : "Pneusol" is a special reinforced soil made of old tyres or parts of old tyres (an industrial waste that is the sourge of Western societies) and natural or artificial ground or wastes.

Le Laboratoire Central des Ponts et Chaussées has developed various forms of this material. When whole heavy-duty vehicle tyres are used, it offers a variety of properties, among them a relatively low weight/volume ratio (approx. 10 $kN/m^{3)}$ for a good light fill, excellent energy absorption to withstand the impact of falling blocks, a flexible, empty structure for a vibration - or earthquake resistant foundation, and so on.

Our paper will deal mainly with the tests and studies carried out and with descriptions of the various structures already made or to be made using this material.

INTRODUCTION

The best possible summing up of Pneusol is "tyres and soils for earthworks" (LONG and POUGET, 1980).

Tyre wastes constitute a population that is diverse and varied in terms of brands, sizes, degree of ageing and wear, the shapes of holes and tears, the internal reinforcements of the treads and beads, etc ... In short, the number of parameters to be studied (were it necessary to study them all) is very great. And such a study would undoubtedly be far from easy : competition among the manufacturers is very keen, and their production secrets (composition of the rubber, types of reinforcements used, etc ...) are closely guarded.

For all these reasons, loading tests on two stacks of tyres will not yield the same stress and strain values. It is here that attentuate the dispersions resulting from the variations in shape and structure among old tyres.

The combinations of tyres and soils produce a great variety of possible Pneusols according to whether one uses passenger-car or truck tyres, uses them whole or partially or completetely cut up (one tread and two sidewalls), uses them joined to form rows or tiers, etc ... (LONG 1984).

Our paper sums up the main tests carried out on light Pneusol made with truck tyres. This is a composite material consisting of tiers of truck tyres and fill.

1 - THE TESTS CARRIED OUT

Three 30-m^2 (5 x 6 m) test structures, built in three layers and instrumented, have been set up at the Centre d'Expérimentations Routieres (C.E.R.) at Rouen. Two Pneusol structures using different designs are subjected to dynamic loadings and compared to a reference structure built without tyres. Measuring instruments have been placed with a view to understanding the behaviour of the Pneusol, in particular as a function of the arrangement of the tyres. The tests carried out, and the placement of the measuring instruments, vary from structure to structure. In some tests, the aim is to understand the attenuation of the forces and accelerations resulting from the presence of the tyres, in others, the influence of the placement of the tyres (instruments placed inside the volume enclosed by the rims, etc ...).

2 - DESCRIPTION OF THE MATERIALS USED

Sand : The sand used in building the three test structures is a silty sand having a 0/10-mm grading, a water-sensitive soil that must be placed under conditions close to the Normal Proctor Optimum when it is used in embankments. The main properties of this material are summed up in table 1.

RTR class :	B_2 m
Grading :	d/D = 0/10 mm, 8% under 80μ, 20% over 2 mm
Sand equivalent :	SE = 26, SE' = 29
Density γ s :	26.5 kN/m^3
Normal Proctor : γ	= 20.0 kN/m^3 , W = 8%
CBR :	51

Table 1 : Geotechnical properties of the sand used

Tyres : The old tyres used are truck tyres having the following dimensions :

Outside diameter :	approx. 1.10 m
Inside diameter	approx. 0.50 m
Width :	approx. 0.26 m
Weight :	approx. 40 kg
Apparent density :	approx. 12.4 kN/m^3

They are used as is (without preparation), abutting but not joined, to form the tiers of structures nos. 1 and 3.

Geotextile :

The geotextile incorporated in the structures is Bidim U 34 nonwomen made by RHONE POULENC TEXTILE of continuous all-polyester filaments and has a basis weight of 270 g/m^2 .

The density of the resulting Pneusol is between 6 and 8 kN/m^3, depending, naturally, on the thickness of the intermediate layer.

The notion of light weight is a very relative one, since in our opinion light materials must be compared not on the basis of their densities but on that of the densities of the materials plus the stiffening structures, which are sometimes very heavy in the case of a material that is light and flexible (i.e., has a low modulus).

3 - DESCRIPTION OF THE TEST STRUCTURES

The three test structures built have plan dimensions of 5 m by 6 m and are about 1.30 m thick. Each is placed and compacted in three basic layers 45 cm thick (fig. 1).

Fig. n°1 : Photograph of the test site

Structure 1 : Built in three layers each approximately 45 cm thick (fig. 2), with each layer consisting of a tier of old tyres placed side by side, either on the formation (case of the first layer) or on the preceding layer (case of second and third layers);the second tier of tyres is staggered with respect to the first and third tiers.

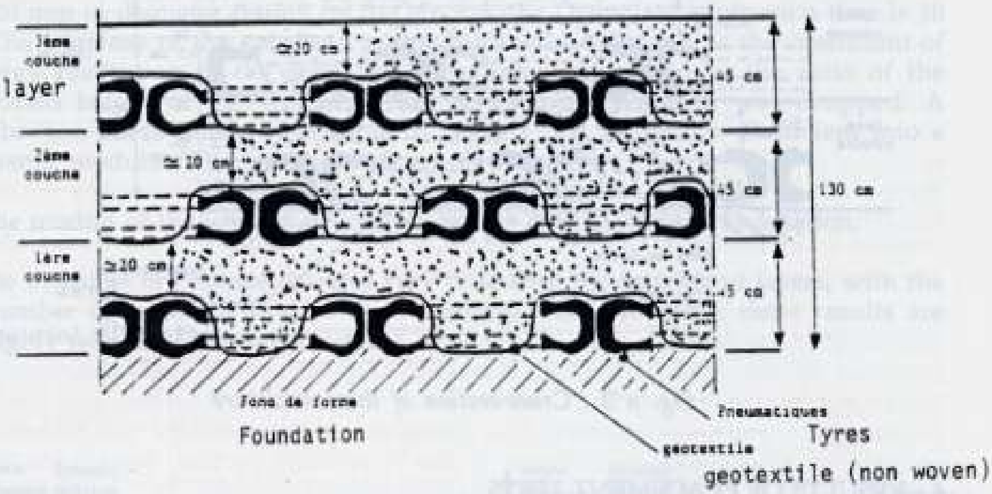

Fig. n° 2 : Cross-section of first structure

The geotextile is laid on top of each tier of tyres and pushed down (by foot) so as more or less to fill the holes. The sand is then placed by loader or hydraulic excavator, working forward, so that the upper sidewalls of the tyres are covered to a depth of about 20 cm after compaction.

Structure 3 : This differs from structure 1 in that the geotextile is placed under each tier. The sand is then placed working forward and compacted.

It is obvious that in this case the only action of the geotextile is to limit contamination. This structure can also be compared to structure n° 1 when they are loaded.

It will be noted that with this structure the volume of voids may be smaller than in structure n° 1, since the sand is not retained by the geotextile and can more readily fill the voids, in particular those inside the tyre. It should also be noted that, during the compaction of the fill, the beads of the tyres tend to close, and that they are in any case not far apart (roughly 5 cm) (fig. 3).

Structure 2 : Structure n° 2 consists of three layers of sand each about 45 cm thick after compaction; it includes neither the geotextile nor tyres and is in fact a reference structure.

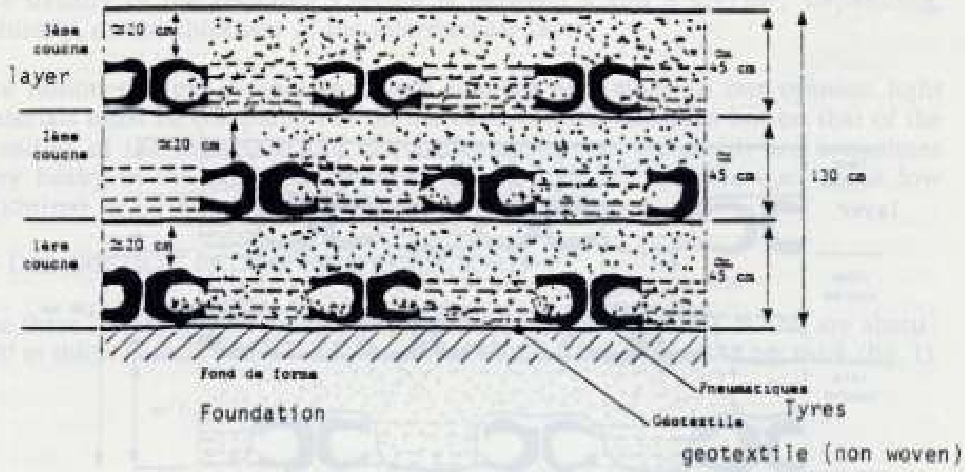

Fig. n°3 : Cross-section of third structure

4 - RESULTS OF PLACEMENT TESTS

Check of Density

Each layer is compacted using a standard, conventional vibrating roller. It was found that on the two Pneusol structures (S1 and S3), the variation of the density inside the rim volume as a function of the number of passes is very slight, with maximum compaction practically reached after four passes. Moreover, the degree of compaction is slightly greater (about 2%) with structures S1 than with structures S3. This difference may be regarded as negligible, so showing that there is practically no fill in the voids left by the inner-tube space. In the case of structure S2, made entirely of sand, the degree of compaction after four passes is equivalent to that of structure S1. On the other hand, the change in the degree of compaction as a function of the number of passes is larger, making it possible to reach nearly 100% after 16 passes of the compactor, as against 98% with structure S1. This change is quite normal, and depends of course on the properties of the material to be compacted.

5 - DYNAMIC MODULI OF THE STRUCTURES

The dynamic modulus is measured using a Dynaplane, an instrument for measuring the deformability of earthwork formations and subgrades.

The apparatus applies to the subgrade to be tested a dynamic loading similar in intensity and frequency to that resulting from the passage of a 13-ton axle at 60 kph, by means of a weight dropped onto a ring of springs mounted on a plate

6,000 mm in diameter resting on the ground; the Dynaplate application time is 20 s. The response of the subgrade to this loading is measured as the coefficient of energy restitution of the shock so engendered, espressed as the ratio of the rebound height of the weight to the height from which it was dropped. A calibration curve makes it possible to convert this restitution coefficient into a dynamic modulus. The tests have shown that (fig. 4) :

- The moduli of the various structures are less than that of the foundation;
- the modulus of Pneusol changes very little with the number of layers, with the number of loadings (first or third loading), and with time; these results are highly relevant to actual structures.

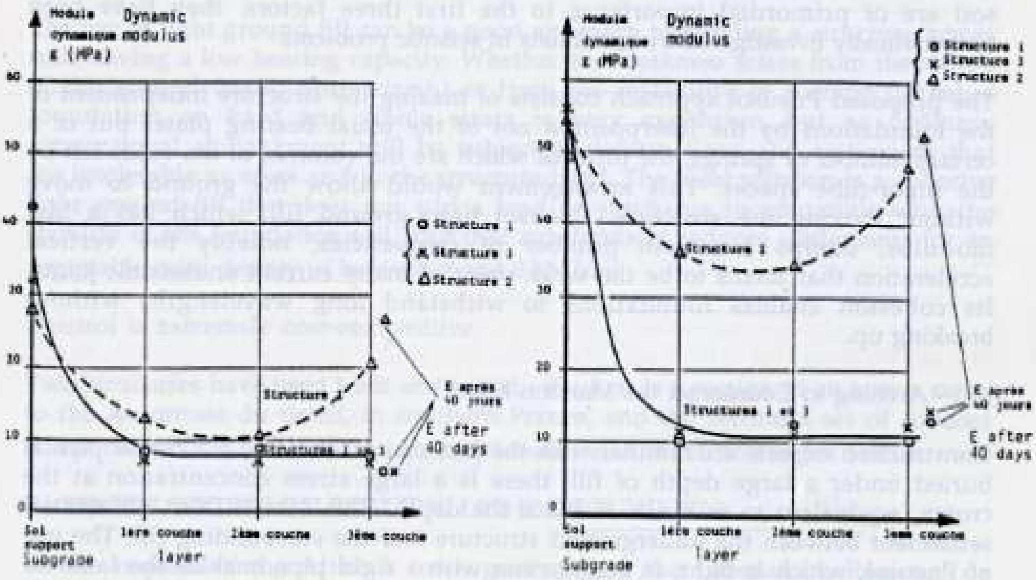

Fig. n°4 : Modulus as a function of structure and number of layers (shown for first and third applications of load)

6 - POSSIBLE APPLICATIONS

These are many and various. We mention a few of these possible applications, which must however still be tested : (see list of structures built).

6. 1 - Vibration resistance

The first results of comparative tests of Pneusol light fill and another fill have shown on the whole that the presence of the tyres results in a significant reduction in the measured accelerations.

This might be explaned first of all by the discontinuity of the medium, since the volume of voids left by the inner tube space is not filled; then by the rather low modulus of Pneusol, of the order of 100 bars or 10 MPa, equivalent to that of a clayey silt; and finally by isolation of the source of vibrations by Pneusol (GUILLARD and AL, 1987).

6. 2 - Earthquake Resistance

The earthquake behaviour of a structure depends on the seismic movement imposed by the ground, on the dynamic response of the structure, on the behaviour of the foundations during and after the earthquake, and on the resistance of the superstructure. The geotechnical properties of the foundation soil are of primordial importance to the first three factors. they have been systematically investigated by specialists in seismic problems.

The proposed Pneusol approach consists of making the structure independent of the foundations by the interposition not of the usual bearing plates but of a certain number of springs, the turns of which are the volumes of the voids left by the inner-tube spaces. This arrangement would allow the ground to move without moving the structure. Pneusol light ground fill, which has a low modulus, damps a certain number of frequencies, notably the vertical acceleration that seems to be the weak point of many current antiseismic joints. Its cohesion enables foundations to withstand long wavelengths without breaking up.

6. 3 - Arching to Counteract the Marston Effect

Construction experts are familiar with the fact that when a rigid concrete pipe is buried under a large depth of fill, there is a large stress concentration at the crown, equivalent to as much as twice the depth. This results from differential settlement between the underground structure and the surrounding fill. The use of Pneusol, which is light, in conjunction with a rigid pipe enables the latter to behave as a "flexible pipe" because of the arching the results from the difference in modulus between the Pneusol and the fill.

The Monistrol work in the Haute Loire, built in 1985, which is 137 m long, as a span of 5.10 m, and is buried under 13 m of fill is the first application of this type (DANTEC and AL, 1987).

Measurement results have confirmed the designers' thinking. Since then, two other structures using this technique have been built in France (Sayat bridge, Banacho culvert...) and twelve in Algeria (Ain Temouchent).

6. 4 - Energy Absorption

The idea of Pneusol as an "energy absorber" springs from a commonplace observation of daily life. One often sees tyres placed casually against garage walls. And tyres are used at tricky corners on motor racing circuits to slow the occasional car that spins off the track. Tyres are also hung, singly or grouped on a wooden plank, along dock walls, to soften impacts by ships.

The first test results showed that the energy restitution coefficient of Pneusol is very low, about 0.10 (this is the ratio of the rebound height H of a falling weight to the height Ho from which it was dropped). This means that Pneusol restores very little impact energy and has a very large absorbing power.

This material has been used on the avalanche protector at La Grave - the Pneusol is 1 m thick (LONG, 1984).

6. 5 - Light Ground Fill

The use of light ground fill can be a good approach to building a structure across soils having a low bearing capacity. Whether the weakness arises from the nature of the ground (mud, peat, marsh) or from the instability of a slope (scree), a foundation on hard and stable strata is very expensive, but an ordinary conventional embankment will be subject to deformations and settlement that are intolerable to users and to the structure itself. The ideal solution is a cohesive light ground fill that does not add a load or surcharge incompatible with the stability of the foundation soil, and that substantially reduces settlements for an acceptable extra density of between 6 and 8 kN/m^3.

Pneusol is extremely cost-competitive

Two structures have been built and tested : the first is a section of an access ramp to the Autoroute du Soleil, in southern France, and the second a set of covered tennis courts (800 m^2) built on sanitary landfill at Altkirch in eastern France.

7 - TENNIS COURTS ON PNEUSOL LIGHT GROUND FILL

At the request of the Altkirch town government, the Laboratoire Régional de l'Equipement de Strasbourg conducted a soil survey of the site of the town's planned covered tennis courts.

The site is a former sanitary landfill (15 years old) consisting in part of silty soils and miscellaneous masonry rubble, but also of houseld refuse.

The boundaries of the landfill were located and its geotechnical properties were determined by :

- five borings by continuous auger;
- five penetrometric borings;

- four borings by excavator to determine the geological cross-section of the first two metres;
- and resistivity profiles to determine as accurately as possible the boundaries of the landfill consisting of household refuse.

A previous study by a private laboratory had reached the conclusion that the tennis courts could not be built.

Analysis of the results of the various tests gave a better idea of the boundaries of the landfill and of the properties of the deposits.

This campaign of borings and tests led to the conclusion that the maximum thickness of the dumped materials was 3.50 to 4.70 m.

The landfill was extremely heterogeneous both in thickness and in the quality of the materials : there was a bit of everything (household refuse, other wastes, even old tyres!).

From the point of view of the optimum layout of the structure, it was found that part of the project would have to be built on a rather compressible zone.

We recommended starting by preliminary stabilization by preloading of the whole zone of low bearing capacity, then excavation down to the project level.

The exacavated materials could then be re-used elsewhere (stands on an embankment using Pneusol, for example).

The preoloading, for which any materials, laid down without compaction, could be used, had to be to a height of at least 2 m, and settlement was to be monitored by level measurements to determine the stabilization time.

We recommended then building a playing area structure of reinforced earth with a flexible surface of the clay type, and applying the final surface only after one or even two years of observations.

Finally, we recommended Pneusol light ground fill on all parts of the tennis courts that were to be built on "poor ground", i.e. the landfill - about 800 m^2. Figure 5 shows the arrangement of each layer of truck tyres.

The Pneusol embankment was built as follows :

The natural foundation soil was excavated down to the planned project level.

Since it was made up of various wastes, it was then cleaned of large blocks that might form hard spots (refrigerators and the like), then compacted to limit the settlement resulting from the bulking during excavation.

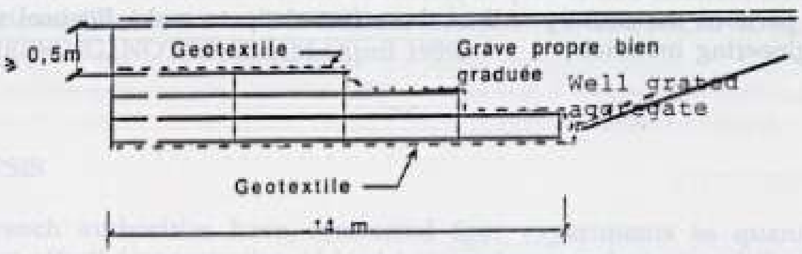

Fig. n° 5 : Cross-section of tennis courts built with Pneusol

On this base, the tyres were laid flat in an orthorhombic array (minimum of voids), then covered with a flexible geotextile (Bidim), placed loosely and pushed down to take the shape of the tyres, and finally filled (including the holes in the tyres and the gaps between them) to a total height of 35 cm .

When a tennis court straddled two zones (partly on natural ground and partly on landfill) and there was a risk of differential settlement, a grill was added at the boundary between the two zones before the tyres were laid down. But it should be noted that Pneusol (with Bidim) already amounts to a reinforcement of the ground.

This structure based on truck-tyre Pneusol has the following advantages :

- a substantial weight reduction (about 25%);
- a good adjustment to differential settlements;
- strengthened cohesion at the level of the various tiers of tyres,and at level of the first and last, linked by a high-density geotextile.

There has been no deformation since these tennis courts were built.

CONCLUSIONS

The primary aim of the tests currently being carried out on various possible applications of Pneusol light ground fill is to determine its properties. Originally designed with truck tyres alone, it can also be used in conjunction with geotextiles or welded wire mesh. The results obtained are positive and quite appropriate for the intended applications. With its low density (6 to 8 kN/m ^{3}) and substantial energy and shock-absorbing power, as tested by the Dynaplane, Pneusol light ground fill is suitable for many uses. Already, eighteen structures habe been built in France (1986), and twelve in Algeria. These structures have behaved very well up untill now, after passing a number of especially hard winters (list attached). Some of them are being permanently monitored as experimental structures.

This material is, generally, very easy to use. Its cost is quite economical. Old tyres, a local material that is very abundant in industrialized countries, are available in all parts of the country. All of these facts help to make Pneusol a good civil engineering material.

CREATION OF ARCHING (PNEUSOL AND OTHER TECHNIQUES)

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SYNOPSIS

The French authorities have conducted four experiments to quantify the "Marston effect" (concentration of loads) on underground pipes and the arching created by the use of a lightly compacted material or of Pneusol.

INTRODUCTION

All builders know that when a rigid concrete pipe is buried under a large depth of fill, there is a significant load concentration at the crown - the load may be as much as twice that corresponding to the height of earth (Marston effect). Above a metal culvert, on the other hand, when a certain height of fill is exceed, there is arching, i.e. a transfer of the loads to the adjacent fill resulting from deformation of the culvert. Shear stresses develop in two vertical planes flanking the section of the structure; in the case of a rigig pipe, these stresses are directed downwards, while in that of a flexible culvert they are directed towards the free surface.

This effect has been investigated by many researchers. Several techniques may be used to relieve the stress concentration, all based on the same principle : promoting differential settlement by incorporating a flexible material having a lower modulus than the fill. The materials used have included straw, uncompacted or lightly compacted fill, Pneusol, and so on.

Our paper presents the results of four experiments carried out on concrete pipes buried under large depths of fill. The primary aim of the first two (Baud, la Sionne) was to quantify the Marston effect, that of the other two to quantify arching achieved using lightly compacted fill and Pneusol Carcal, Monistrol-sur-Loire).

1 - EARTHWORKS

The work at Monistrol-sur-Loire is an embankment made using whole tyres (truck tyres here) laid side by side, with fill in the volume inside the "rims"; successive layers that may or may not be staggered.

The design work consists of determining, from the known mechanical properties of the Pneusol and of the adjacent fill, the thickness the Pneusol structure must have to ensure substantially constant total settlement along the top of the embankment.

Placement is relatively simple. Generally, the first layer is placed with the truck tyres touching one another (orthorhombic array) when the fill reaches a height of 50 cm above the structure. The tyres are filled so that equipment and personnel can travel on them. The operation is repeated, with each layer staggered a half-diameter with respect to the one before.

Given the difficulties of measuring stresses in soil (reliability of instruments, dispersion of readings, longterm behaviour, precision, etc ...), our only course is to use familiar, conventional instruments. We attempt, insofar as possible, to use a large number of sensors.

2 - EXPERIMENTS

Example 1 : Baud precast arch culvert

The work consists of a precast barrel vault having a radius of 5.2 m, to 0.35 m thick, supported by two abutments 2 m high and 0.7 m thick, resting on flanges 3.2 m wide and 0.7 m thick. Five pressure sensors were placed in the inner fill and two in the outer fill.

It can be seen from the pressure curves at three covering heights that the "Marston" effect shows up at the haunches and not at the crown. This may be explained by some flexibility of the vault. Globally, integration of the pressure diagrams shows a mean pressure on the vault equal to 1.25 times the vertical earth pressure, close to the theoretical value of 1.2 times (fig. 1).

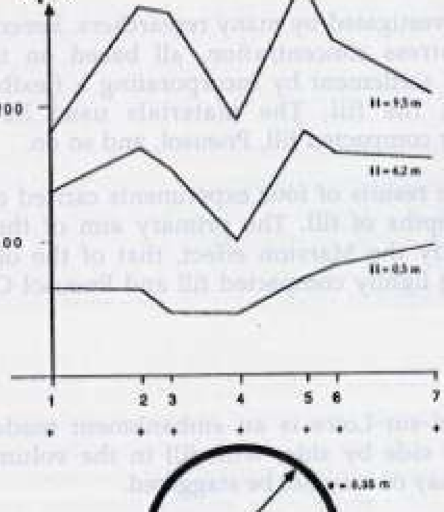

Fig. n° 1 : Arched culvert at Baud

Example 2 : La Sionne culvert

The work consists of two precast ogival half-shells 0.35 m thick, bearing against one another at the crown and supported at the base by an invert 1 m thick. Its interior width is 4.2 m, its interior height 3.8 m . The covering height is 22.5 m . Six pressure sensors were placed on two parallel profiles in the inner fill.

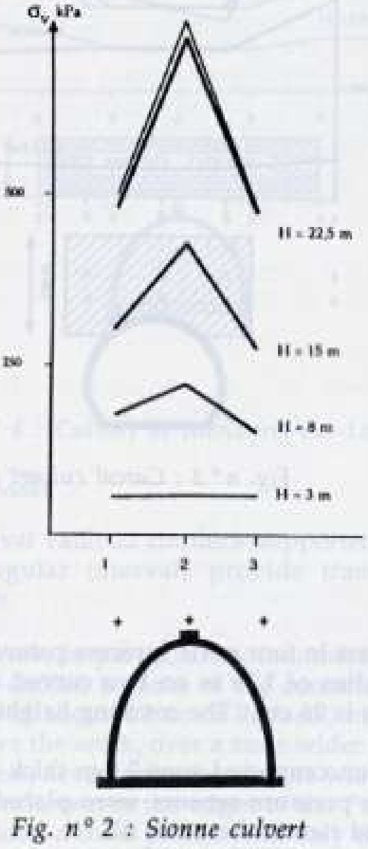

Fig. n° 2 : Sionne culvert

The shape of the mean pressure curves for the two profiles at three covering heights shows that the "Marston" effect first appears between 3 and 8 metres and is greater on the crown than on the haunches. This may be explained by the presence of two runners tying the elements together. A further measurement, made later, revealed a slight aggravation of the effect (dashed curve). The mean pressure on the horizontal plane above the vault is equal to 1.5 times the vertical earth pressure, rather close to the theoretical value of 1.66 (fig. 2).

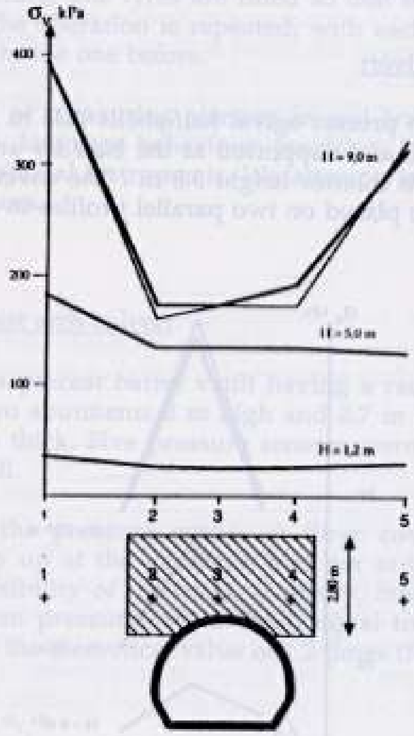

Fig. n° 3 : Carcal culvert

Example 3 : Carcal

The work is a pipe precast in four parts (process patented by Matière) : a quarter-circle vault having a radius of 1.25 m on two curved abutments keyed in situ to the invert. The thickness is 26 cm . The covering height is 9 m .

A lightly compacted or uncompacted zone 2.8 m thick was incorporated in the fill for pressure relief. Five pressure sensors were placed in each of three profiles, three in the inner fill and two in the outer fill.

The pressure diagrams show that the desired relief appears only at a covering height of 5 metres and is substantial at the final height of 9 metres. The mean pressure on the horizontal plan of the inner fill overlying the work is equal to 0.9 times the vertical earth pressure. If a conventional fill had been used, the theoretical value would have been 1.6 times. A further measurement made three years later (dashed curve) shows that the effect is lasting (fig. 3).

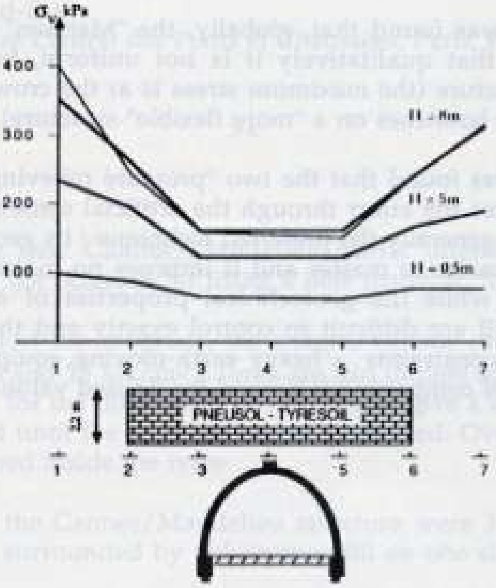

Fig. n° 4 : Culvert at Monistrol-sur-Loire

Example 4 : Monistrol-sur-Loire

The work consists of an ogival vault 22 cm thick supported by two sills resting on micropiles. Runners at regular intervals provide transverse stiffening. The covering height is 11 metres.

To avoid overloading the work, in particular its foundation, pressure relief using the Pneusol technique was chosen because of the consistency of its geotechnical characteristics. A thickness of about 2.2 m of Pneusol, made using six layers of truck tyres, was placed above the work, over a zone wider than the work itself. To test the efficacy of the process, seven pressure sensors were placed in each of two profiles : three above the work, two at the edges of the Pneusol, and two outside the Pneusol. To this was added a third profile with only three sensors (one in the centre, two outside).

The pressure curves show that the desired effect appears immediately with the first placement of fill above the Pneusol. The ratio of the mean vertical pressure on the work to the vertical earth pressure is about 0.8 here, whereas the theoretical value for a conventional fill is 1.6 . The measurement made eight months later (dashed line) shows that the effect is relatively stable (fig. 4).

CONCLUSIONS

We may make the following comments on the four experiments :

In the first two, it was found that, globally, the "Marston" effect is confirmed quantitatively, but that qualitatively it is not uniform, but depends on the "rigidity" of the structure (the maximum stress is at the crown on a "very rigid" structure and on the haunches on a "more flexible" structure).

In the last two, it was found that the two "pressure relieving" techniques could cancel or even reverse the effect through the artificial settlement induced in the inner fill. Pneusol is generally the preferred technique : its geotechnical properties and placement are easier to master and it imposes no major constraints on the construction work, while the geotechnical properties of an uncompacted or lightly compacted fill are difficult to control exactly and the use of such a fill imposes significant constraints - heavy earth-moving equipment cannot travel on it without a risk of compacting it beyond the desired value.

CANNES/MANDELIEU EXPRESSWAY : "PNEUSOL" LIGHT GROUND FILL

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SYNOPSIS

Construction of the new Cannes/Mandelieu traffic interchange in southeast France has provided the occasion for using a new material, "light Pneusol".

Including the weight of the subgrade, the weight/volume ratio of fill is reduced to values between 10 and 15 kN/m^3 . Tyres are laid in tiers separated by layers of soil that compensate for the differences in tyre size to give a smooth surface. This operation is repeated until the required height is reached. Overall lightness is the result of the air trapped inside the tyres.

Final dimensions of the Cannes/Mandelieu structure were 3 m high, 6 m wide, and 80 m long. It is surrounded by polystyrene fill on one side and ordinary fill on the other.

This innovative technique is being monitored very carefully using measuring equipment embedded in the three types of fill subjected to actual traffic use.

INTRODUCTION

The use of lightweight fills opens up interesting approaches to building across soils of low bearing capacity. Whether the weakness results from the nature of the ground (silt, peat, marsh) or from the instability of a slope (scree), building foundations down to hard, stable strata is very expensive, while an ordinary conventional embankment will be subject to deformations and settlement that neitheir users nor the structure itself can tolerate. In many cases, the ideal solution is a light fill that avoids adding a load incompatible with the stability of the underlying soil or of nearby structures and that substantially reduces settlement for an acceptable extra cost.

The difficulty lies in finding a low-cost lightweight material. There are a number of light materials, from fir and pine bark to polystyrene foam. The latest is Induplast, a polypropylene honeycomb structure. The main drawback of these modern materials is their rather high cost; they may also be very fragile. The cost criterion led us to turn to the use of a very abundant waste material found in all built-up parts of industrialized countries - old tyres. The notion of light weight is a relative one, since, in comparing light materials with one another, we think that one must take into account not their specific apparent density, but that of the material plus any reinforcing structures (slab, thicker subgrade, heavier pavement). The cost of the material must also be considered in the light of this possible extra cost.

Our paper deals with the construction of an experimental section of light Pneusol (Long et Al, 1987) on the Cannes/Mandelieu interchange of the Esterel-Côte d'Azur motorway (ESCOTA) in southern France; this embankment is an extension of a lightweight embankment having a polystyrene core.

1 - GEOLOGICAL AND GEOTECHNICAL ASPECTS OF THE SITE

In connection with plans to improve the Cannes/Mandelieu interchange and widen the Esterel motorway to two x three lanes, ESCOTA and SCETAUROUTE investigated the use of polystyrene as a fill for widening the motorway where it crosses the Siagne plain on embankments from 3 to 8 m high for a lenght of about 2 km. It is in the context of this operation that an embankment of light Pneusol 80 m long and having a total height of 3 m (with a subgrade 0.50 m thick) was built.

Laboratory and in situ tests (bore holes and cores, penetration tests, and statistical studies) were carried out to determine the geotechnical properties of the foundation.

a) Schematically, this survey revealed three distinct zones :

- a surface zone of clay and plastic silts having very poor mechanical properties, from 6 to 10 metres thick;

- a zone of fine sand or silty sand having properties that are substantially better, but still mediocre and heterogeneous, 6 to 11 m thick;

- a deep stratum of silt having properties that are poor, but better and more uniform than those of the surface layer.

  At the time of our bore holes (January 1982), the water table was at a depth of 3 metres, but it is quite possible, given the low permeability of the ground, that the hydrostatic level is in fact higher. In any case, during periods of high water, the water table practically reaches the surface of the natural ground.

b) The results of the laboratory tests revealed that the materials are loose and manifestly saturated, since we found :

- in the sands, w = 27 to 30%, γ= 18.4 to 19.4 kN/m^3 ,

γ_s = 26.5 to 26.8 kN/m^3;

- in the clays and silts, w = 32.2 to 43.5%, γ = 6.7 to 19 kN/m^3,

$\gamma_s = 26.3$ to $26.6\ kN/m^3$.

The low density of the sands gives them a significant compressibility, with

$$Cc = 0.119 \text{ to } 0.136$$

$$eo = 0.675 \text{ to } 0.791$$

whence $\frac{Cc}{1+eo} = 0.07$ to 0.08

The compressibility of the clayey-sandy silts is obviously much greater, with

$$Cc = 0.29 \text{ to } 0.46$$
$$eo = 1.00 \text{ to } 1.584$$

whence $\frac{Cc}{1+eo} = 0.15$ to 0.18

c) Tests carried out using the 100-kN Dutch static penetrometer show that the three distinct zones include :

- a surface zone of very weak soft clay, down to a depth lying on the whole between 6 and 10 metres;

In this zone, $q_c = 6$ to $8\ daN/cm^2$.

However, in some parts of the site, the first three metres are even weaker, with $q_c = 4\ daN/cm^2$.

- an intermediate stratum having substantially better, but much more dispersed, properties, where $q_c = 20$ to $50\ daN/cm^2$.

This formation, in which some peak values close to 70 and even 100 daN/cm^2 were recorded , corresponds to the layer of sand detected between the depths of 12.30 and 16.00 m by cores from bore holes.

The large dispersion of the measurements and a few rather low values of q_c reflect sands contaminated by silts. The thickness of this intermediate stratum ranges from about 6 to 16 metres.

- a homogeneous deep stratum where $q_c = 11$ to $12\ daN/cm^2$.

These are silty alluvia of the Siagne, found over the entire interchange area, which extend to a depth not reached by our survey, which could well be as much as about fifty metres.

d) Finally, the site, to be covered by a general embankment about 2 metres thick, will undergo, under the weight of this embankment, absolute settlements of the order of 40 to 50 cm, accompagnied by differential settlements that may reach 10 to 15 cm.

2 - LIGHT PNEUSOL

The light Pneusol embankment built has a total lengh of 80 m and is about 2.50 m high. The access ramps are also made of Pneusol.

The embankment is in two sections that differ in the design of the Pneusol (presence or absence of a geotextile between the tiers of tyres) and of the subgrade (which in one case encloses a geogrille).

It is obvious that when a geotextile is used, none of the fill enters the voids left by the inner-tube spaces. But preliminary tests (LONG et AL, 1987) have shown that the difference this makes is very small, even negligible.

It should be noted that light Pneusol built tier-by-tier, with the tyres staggered between tiers, can partially correct differential settlements.

Each of the sections is built as follows :

a - The natural ground is cleaned without scraping off the topsoil.

b - A base of 0/60-mm crushed materials, 0.20 m thick, is placed on the ground.

c - The tyres of the first tier are laid flat on this base in an orthorhombic pattern (fig. 1), then covered with geotextile or not, depending on the section (fig. 2), and finally filled (rim holes and spaces between tyres) to their thickness (about 25 cm) and compacted.

d - A second tier of tyres, staggered with respect to the first (fig. 1), is then laid down and the other operations repeated, and so on until the top layer of the Pneusol embankment is in place.

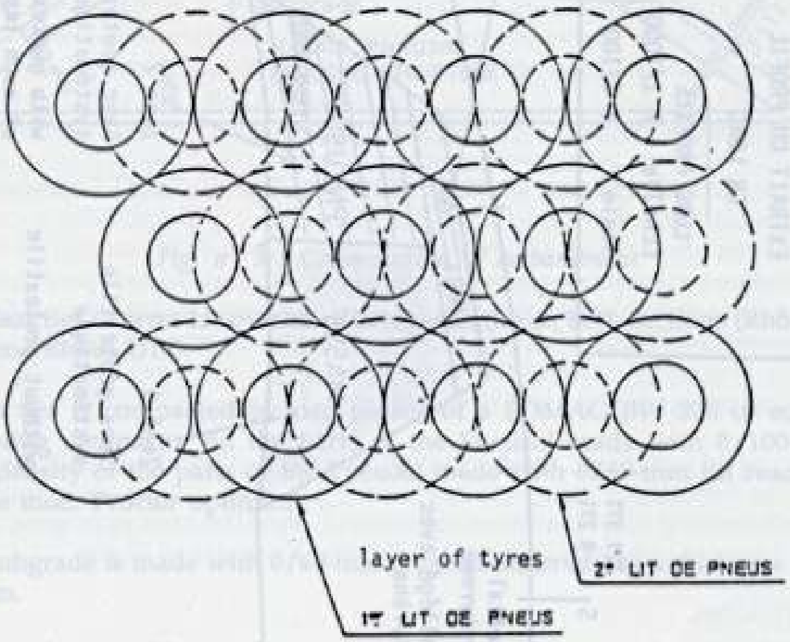

Fig. n° 1 : Arrangement in plan (orthorhombic array)

e - The materials used are :

. a 0/60 mm subgrade type crushed material for the top metre of the Pneusol embankment;

. a 0/100-mm fill for the remainder of the Pneusol embankment, the side slopes, and the access ramps.

f - The slopes of the embankment are built up at the same time as the Pneusol embankment (fig. 3).

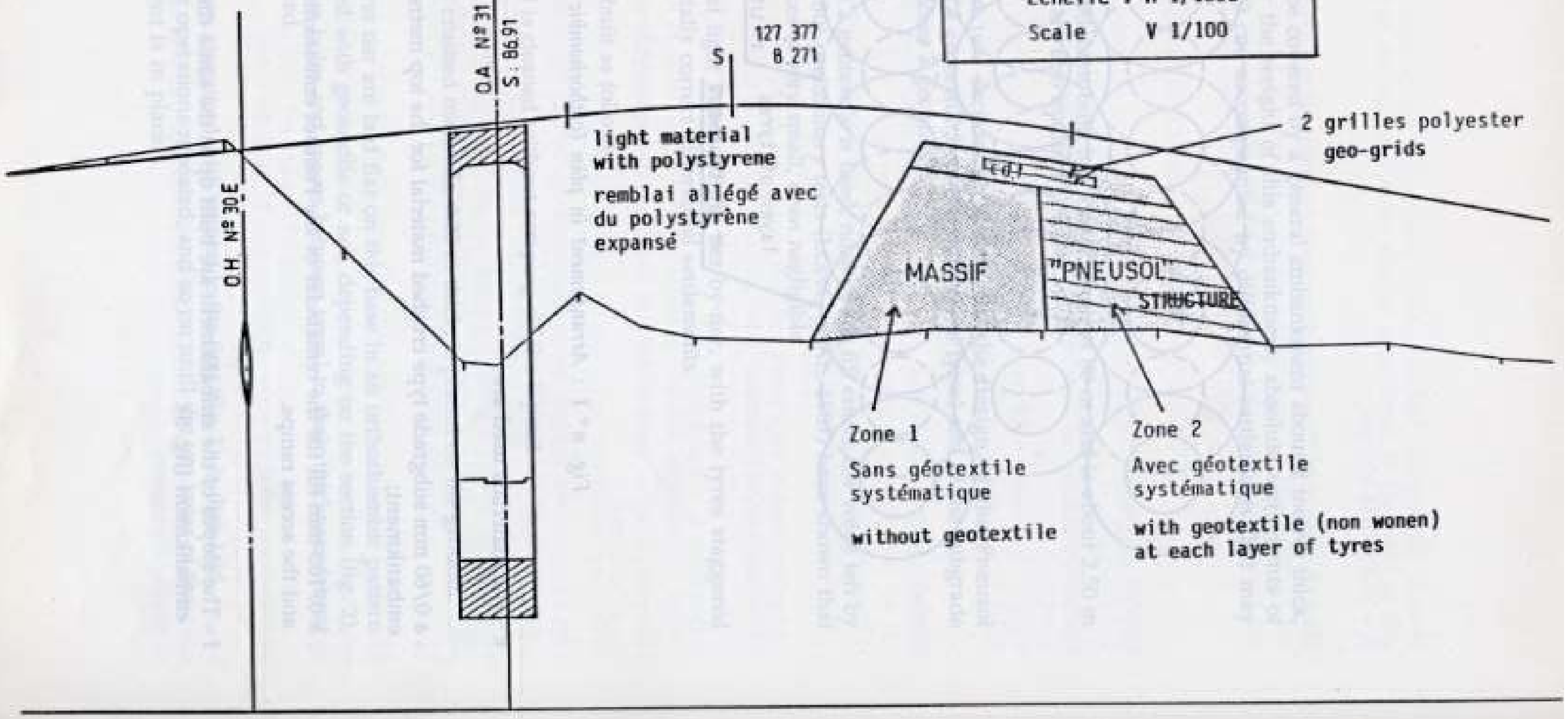

Fig. n° 2

EXTRAIT DU PROFIL
EN LONG

LONG PROFILE
Echelle : H 1/1000
Scale V 1/100

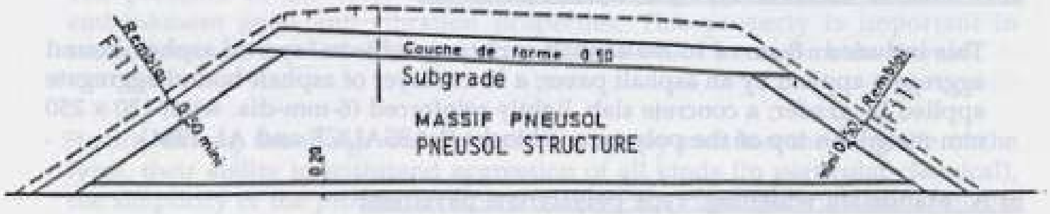

Fig. n° 3 : Cross-section of embankment

g - The last tier of tyres is covered with a geotextile on both sections (Rhône Poulenc Bidim U19).

h - Each tier is compacted by two passes of a BOMAG BW 200 or equivalent vibrating compactor on the parts of the Pneusol made with 0/100-mm fill. The density of the parts of the Pneusol made with 0/60-mm fill reached 95% of the mod. Proctor optimum.

i - The subgrade is made with 0/60-mm crushed materials, to a thickness of about 0.50 m.

Straddling the two 20-m sections made of Pneusol, over a length of 20 m, the subgrade is reinforced by two polyester grilles 0.15 m apart, with the lower grille 0.15 m above the bottom of the subgrade (fig. 2).

The ground under the body of this experimental embankment has been instrumented by the Laboratoire Régional des Ponts et Chaussées d'Aix (settlement meters, pressure sensors, surface levels).

3 - PAVEMENT BUILT ON EMBANKMENT

For pavement design purposes the light Pneusol embankment has a modulus, measured by Dynaplate, of the order of 10 to 12 MPa.

This modulus was determined before the work was done, at an experimental site, using truck tyres covered with 0.15 m of Streff sand (similar to Fontainebleau sand). An embankment of sand only, under the same compaction conditions, has a modulus of the order of 22 MPa (LONG et AL, 1987).

When the subgrade was built, we repeated the plate tests and found that, on both sections and whether or not there were geogrilles in the subgrade, the modulus was about 64 MPa.

These good results made it possible to choose a conventional pavement from among the various types that had been considered, which included :

a) A "Palavas les Flots" type polystyrene pavement

This included : 8 cm of rolled asphalt surfacing; a 12-cm layer of asphalt-bound aggregate applied by an asphalt paver; a 20-cm layer of asphalt-bound aggregate applied by grader; a concrete slab, lightly reinforced (6-mm-dia. wire, 150 x 250 mm mesh), on top of the polystyrene blocks (LASSAUCE and AL 1984).

b) A "Mandelieu widening" type polystyrene pavement

The structure planned by SCETAUROUTE for the standard widening section (right-hand lane, for heavy vehicles) included : a permanent 8-cm rolled-asphalt wearing course; a 7-cm temporary rolled-asphalt wearing course; a 20-cm roadbase of asphalt-bound aggregate; a subbase of unbound 0/31.5 mm aggregate; a subgrade of at least 50 cm of 0/60-mm aggregate; a 15-cm slab, reinforced (6-mm-dia. wire, 100 x 100 mm mesh), on top of the polystyrene.

c - The conventional pavement finally chosen

This type of pavement, used under all standard subgrade conditions, includes : a 7-cm permanent rolled-asphalt wearing course; a 7-cm temporary rolled-asphalt wearing course, a 20-cm roadbase of asphalt-bound aggregate; and a 25-cm subbase of unbound aggregate; for a total thickness of 59 cm.

CONCLUSIONS

The experimental Pneusol embankment at Mandelieu has been opened to traffic, at the end of 1988 and nothing wrong happened since.

In spite of this short time experience some significant findings may be pointed out :

- The mean density as measured by total pressure cells is between 13 and 15 kN/m^3, subgrade included.

- The construction cost found at this experimental site, the first of its kind, is quite attractive - 120 F/m^3 (Pneusol + subgrade) - and compares favourably to polystyrene foam or expanded clay (an average of 250 to 300 F/m^3).

It should however be noted that the mean density of the light embankments built with polystyrene foam or expanded clay for the prices mentioned is less than 10 kN/m^3) (8 to 9 kN/m^3).

In some cases (in particular for embankments on unstable slopes), it is possible to compensate for this difference in mean density by doing additional earthwork and using more Pneusol.

- Globally, the Pneusol embankment behaves as an embankment that is reinforced and therefore has cohesion. This cohesion enables it to withstand much larger differential settlements than a conventional embankment.

- The presence of the tyres and of the voids they create gives the Pneusol embankment good anti-vibration properties. This property is important in some cases, and has led to the building of a section of a tram line on Pneusol.

- Finally, among the things we are sure of, we may mention the long life of the tyres, their ability to withstand aggression of all kinds (in particular chemical), the simplicity of the process, its univerticality - the basic materials are available practically on the spot in all countries -, and, of course, its ecological character - wastes are not only eliminated, but also made useful in the process.

The Pneusol test embankment at Cannes/Mandelieu is not yet in actual use, so that not all of the information to be derived from this experiment is currently available : it will be interesting to follow the behaviour of the conventional pavement planned and to be able to compare it with that of the nearby pavement on a light embankment made with expanded clay.

PNEUSOL TO REDUCE ACTIVE EARTH PRESSURE

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IV COLLOQUE FRANCO-POLONAIS, Grenoble (Sept. 1988)

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SYNOPSIS

"Pneusol", a combination of old tyres and soils, is a technique developed by the L.C.P.C. that has a variety of uses : retaining structures, slope reinforcement, lightweight embankments, protection of banks of waterways, arching effect, etc...

"Pneusol" can be placed behind a retaining wall to reduce the active earth pressure on it. Tests on a small-scale model have demonstrated the influence of this "reducing" effect on the critical height of the structure. The influence of the spacing between the layers of tyres and the number of tyres per layer has been investigated.

INTRODUCTION

Pneusol, made of tyres or tyres parts and soil, has many applications. To date, more than 62 structures have already been built in France, including one in which Pneusol is used to reduce the active earth pressure behind a retaining wall (54 m. long, 5 m. high, 4 m. thick) founded on piles (LONG, 1985) and five similar structures built since then.

We present the first investigations of "active earth pressure reducting Pneusol", carried out on a three-dimensional small-scale model at the INSA of Lyon. The drawbacks of such a model, in particular the difficulty of preserving similarity relations, are well known. The aim of this first stage of research was to obtain qualitative results sufficient to reveal the influence of certain parameters. The tests we report simulate the presence of Pneusol behind a cantilever retaining wall.

1 - DEFINITION OF ACTIVE-EARTH-PRESSURE-REDUCING PNEUSOL

An obvious fact of geotechnics, that the active earth pressure of a coherent soil is quite low because of its very cohesion, suggests that (judiciously) reinforcing a soil may be a good way of reducing its active earth pressure, provided that the cost and difficulty of the operation are not prohibitive. Pneusol would seem in principle to satisfy these conditions, since old tyres are a common waste material in our industrialized societies .

Truck tyres are best in practice, because they are bulkier and require less manpower for placement.

2 - EXPERIMENTAL ARRANGEMENT (Fig. 1).

The aim of the experiment was to investigate, in qualitative terms, the influence of Pneusol placed behind a cantilever retaining wall on the stability of the retaining wall. A small-scale model, placed in a rectangular container 80 cm high, 80 cm wide, and 120 cm long, was used.

The wall, extending over the width of the container, consisted of three identical elements, separate so as to eliminate edge effects. Wall displacements were measured only on the centre element. The shell of each element was 24 cm wide and 70 cm high, and the base was 24 cm wide and 12 cm long. The heel projected 85 cm. A strip of polyane constituted a flexible joint to ensure tightness while preserving the independence of the elements.

The "tyres" used were annular rings of polyurethane foam, 12 mm thick, with an inside diameter of 30 mm and an outside diameter of 60 mm (about 1/20th the size of a typical truck tyre).

The soil used in the Pneusol and in the fill was a crushed sand having a uniform grading (Dmin = 0.3 mm; Dmax = 1 mm). It was placed at a constant density of 1.43.

The wall rested on a rigid foundation and its displacement was monitored by two comparators having a precision of 0.01 mm.

The nature and geometry of the wall, the sand, and individual tyres were constant; the parameters whose influence was investigated concerned the composition of the Pneusol : the spacing "e" between layers of tyres (i.e., the thickness of sand between two layers) and the number "n" of tyres in each layer.

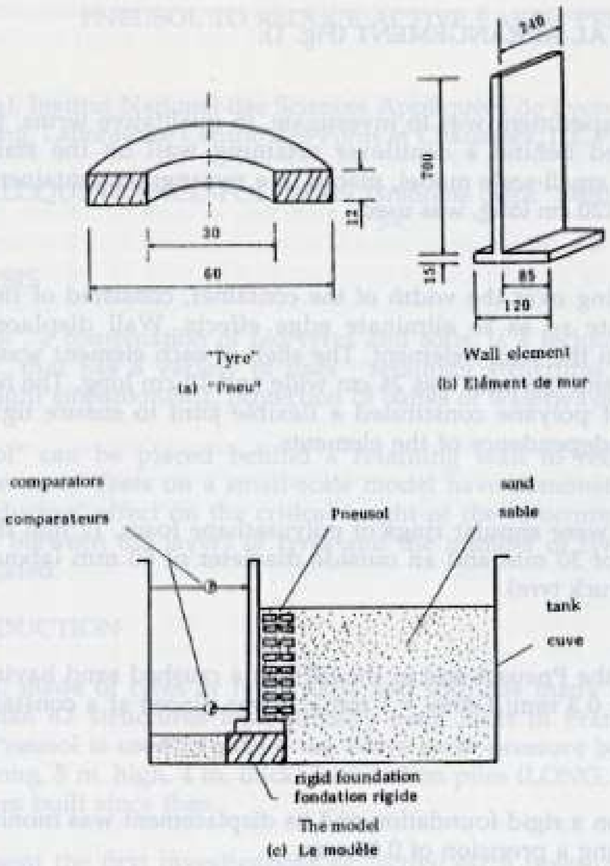


Fig. n° 1 : The experimental model (dimensions in mm.)

For each case investigated, the displacement of the wall was measured as the placement of the Pneusol and fill progressed.

3 - RESULTS OF TESTS

The results of the measurements were used as is to plot the curves h = f (Δl) representing the height of fill behind the wall versus the displacement of the wall.

3.1. Sand alone

This test was used to produce the reference curve (fig. 2) to which the curves for the various types of active-earth-pressure-reducing Pneusol were compared. This curve shows negative displacements of the wall, explained primarily by the stabilization, during the placement of the first lift of fill, of the base on the foundation block, which was somewhat uneven. These artifacts disappear only when there is a sufficient surcharge on the heel; they were found in all of the tests carried out, but do not affect the analysis of the results.

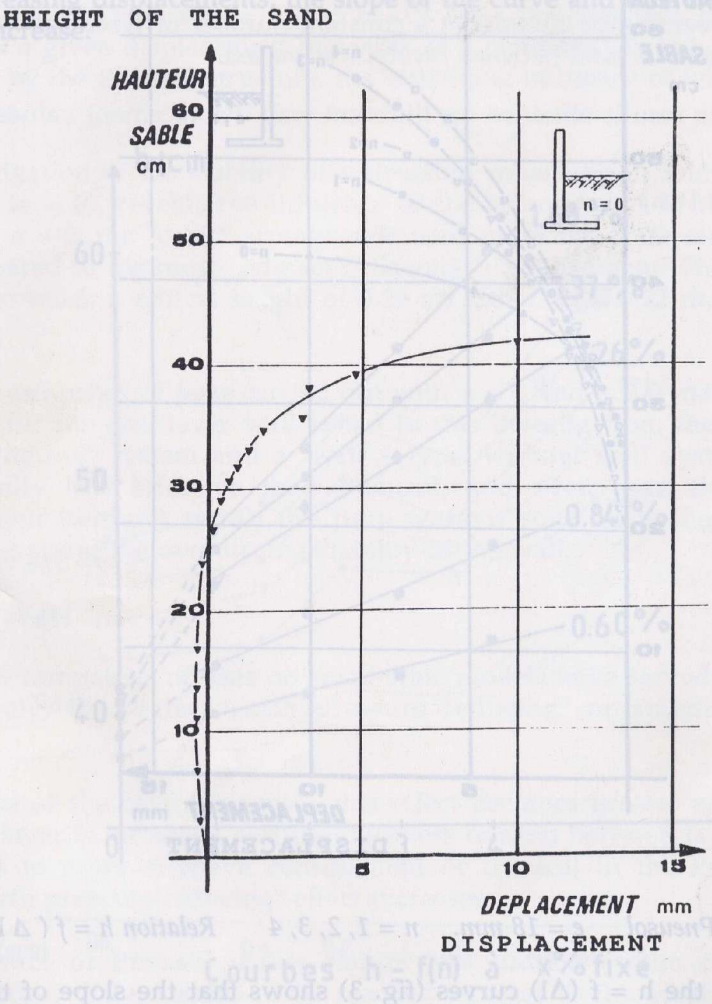


Fig. n° 2 : Sand alone (n = o) Relation h = f (Δl)

This curve is similar to the shear curve of a loose sand. Above a certain height of fill, the displacements become larger as the successive layers of sand are placed and the critical failure height of the structure is approached.

3.2. Wall with active-earth-pressure-reducing Pneusol

This series of tests investigated the influence of the number "n" of tyres per layer at a constant layer spacing of 18 mm. The simple cubic assembly of each layer included 4 tyres in contact with each wall element and consists of (n x 4) tyres. The values of n investigated ranged from 1 to 4.

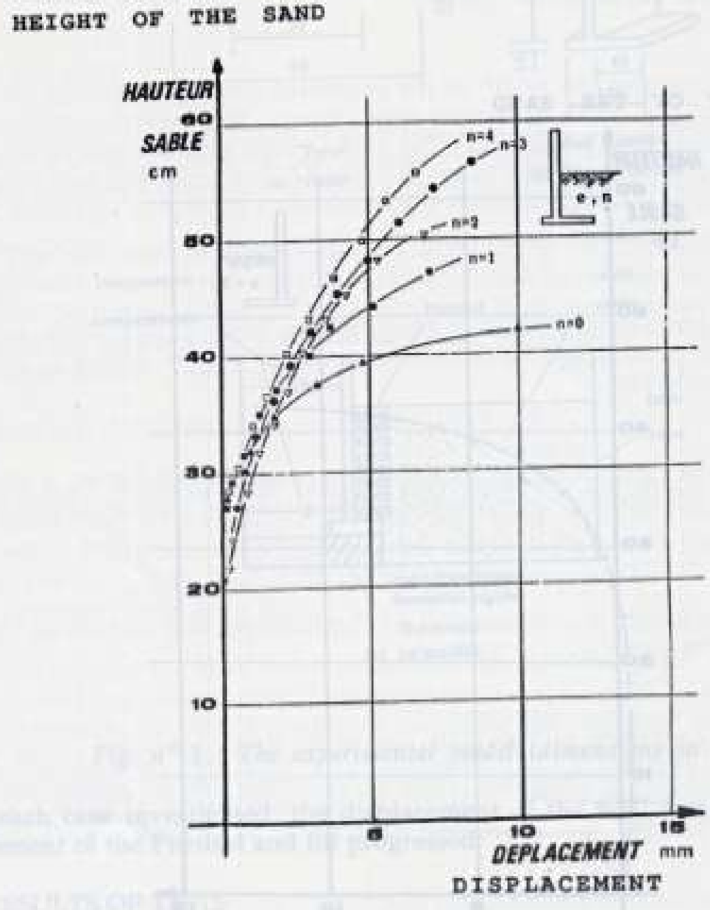


Fig. n° 3 : Pneusol e = 18 mm. n = 1, 2, 3, 4 Relation h = f (Δl)

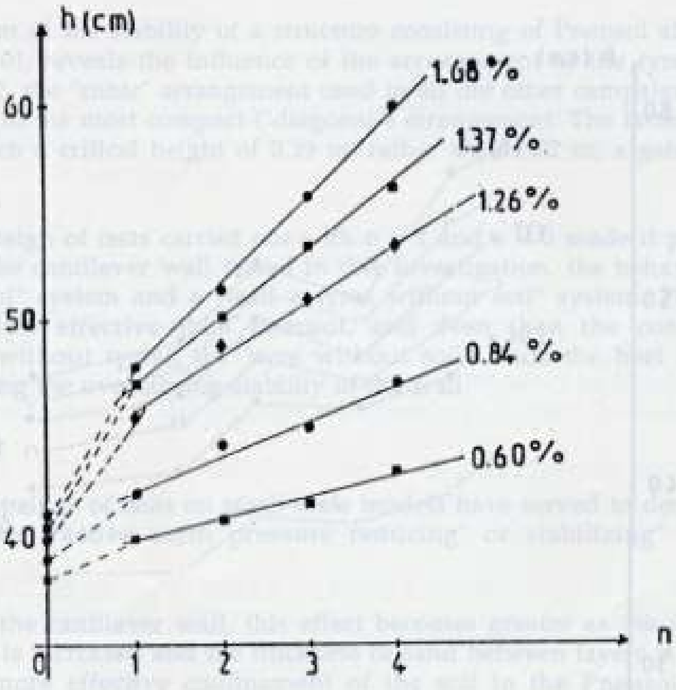
A comparison of the h = f (Δl) curves (fig. 3) shows that the slope of the curve increases with the number n of tyres and that for n = 3 and 4 the curvature becomes very small over the range of fill heights tested. Similary, it can be seen that below a certain height of fill, of the order of 250 mm, the number of tyres has no influence, which is logical since the displacement of the wall without Pneusol is very small. On the other hand, as the critical height is approached, the Pneusol effect substancially diminishes the displacement. The failure of a wall without

Pneusol, or with n = 1, is sudden, whereas deformation becomes gradual when n > 1.

The relation between the displacement of the wall and the height of Pneusol and fill for each number n of tyres is illustrated in figure 4. The displacements are stated in per cent, as the tangent of the angle of rotation of the wall with respect to its base. It can be seen that :

- the height of fill at which a given displacement is reached is a linear function of n; the greater the number of tyres, the greater the height of fill;

- for increasing displacements, the slope of the curve and thus the gain in fill height increase.



Courbes h = f(n) à x% fixé
pour e = 18 mm
Curves h = f (n) with constant x % and
e = 18 mm

Fig. n° 4 : Pneusol (e = 18 mm.) Relation h = f (n) versus rotation of wall (x%)

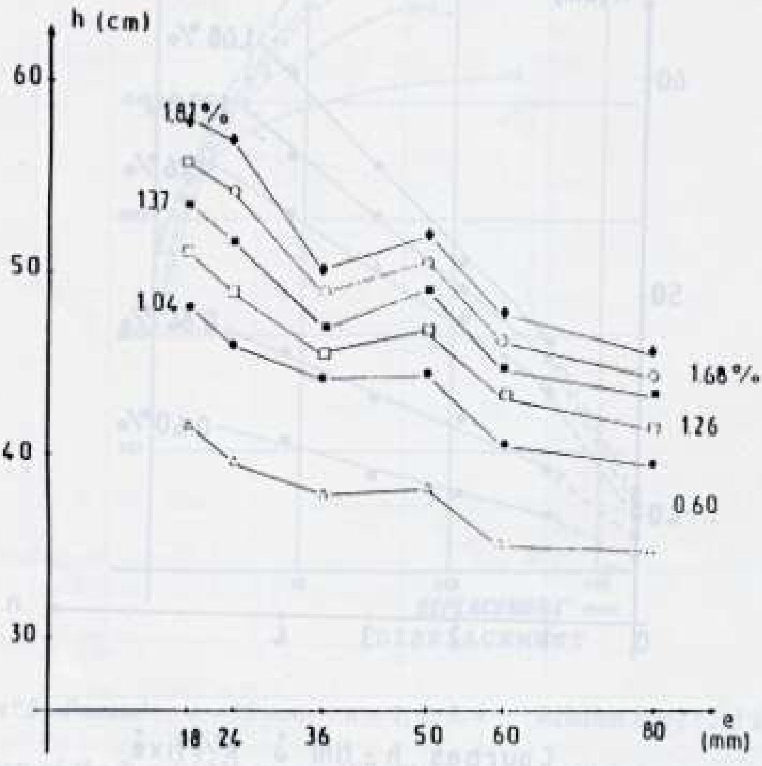
Thus, when the number of tyres per layer is varied, we find that, the greater the admissible displacements of the wall, the more advantageous it is to use Pneusol.

It can be seen that the measurement points for sand alone (n = 0) are not located on the straight lines characteristic of the presence of Pneusol. The placement of the Pneusol alters the character of the fill behind the retaining wall and thus its behaviour. The Pneusol contributes a sort of "cohesion" that reduces the actice earth pressure on the wall; in addition, it is in itself a more deformable structure, so reducing the active earth pressure exerted on the wall by the unreinforced sand behind it.

3.3. Influence of spacing between layers of tyres

The spacing between layers containing a constant number of tyres per layer (n = 3), i.e. the thickness e of sand between layers, was varied.

Figure 5 shows the results obtained for different wall displacement values.



h : f (e) à x% fixé pour n=3

h = f (e) with constant x % for n = 3

Fig. n° 5 : Pneusol (n = 3) Relation h = f (e) versus rotation of wall (x%)

It can be seen that, the smaller the spacing, the greater the height reached by the fill at a given displacement. As e decreases, the Pneusol tends to act as a gravity structure juxtaposed on the cantilever wall.

One again, the greater the admissible displacement of the wall, the larger the influence of this reduction in spacing. However, the measurement points show a unexplained discontnuity at e : 50 mm (the reproducibility of the test has been confirmed).

3.4. Other results

Tests were carried out with no sand ($e = 0$) between the layers. The results obtained, for the values $n = 1$ and $n = 2$ only, confirm that the height of fill reached at a given displacement increases as n increases : in this case, the wall is stabilized by the Pneusol structure, the stabilizing influence of which increases as n increases.

An investigation of the stability of a structure consisting of Pneusol alone, built vertically ($e = 0$), reveals the influence of the arrangement of the tyres in each layer. For $n = 2$, the "cubic" arrangement used in all the other campaigns of tests was compared to the most compact ("diagonal") arrangement. The latter makes it possible to reach a critical height of 0.29 m, rather than 0.22 m, a gain of more than 30%.

Finally, a campaign of tests carried out with $n = 1$ and $e = 0$ made it possible to compare, for the cantilever wall tested in this investigation, the behaviour of a "wall + Pneusol" system and a "wall + tyres without soil" system. This last is substantially less effective than Pneusol, and even than the conventional embankment (without tyres); the "tyre without soil" loads the heel much too lightly, impairing the overturning stability of the wall.

CONCLUSION

These first campaigns of tests on small-scale models have served to demonstrate, qualitatively, the "active earth pressure reducing" or stabilizing" action of Pneusol.

In the case of the cantilever wall, this effect becomes greater as the number of tyres per layer is increased and the thickness of sand between layers is reduced : this leads to more effective confinement of the soil in the Pneusol, and the "active earth pressure reducing" effect increases.

The presence of Pneusol makes failure less sudden as the critical height is approached, and the heights of fill reached increase as the admissible amplitude of displacement of the wall increases.

The experimental results presented cover only a mass of loose sand and Pneusol placed with no ties between the tyres, in which the "reinforcement" effect is absent. The tyres used in the model represent solid tyres. Later tests should make it possible to investigate, in particular, the influence of the shape of the tyre (more flexible hollow tyre, tyre without sidewalls) and ties between the tyres.

The influence of Pneusol on a gravity wall will also be investigated.

ACKNOWLEDGMENTS

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REFERENCES

- LONG N.T., POUGET (1980), "Le renforcement des sols par des pneumatiques usagés". Rapport à la DGRST, Septembre.

- CARTIER G., LONG N.T., POUGET P., BARGILLAT R., CUDENNEC J.-P. (1981), "Déchets urbains et pneumatiques usagés en Génie Civil".- X[e] Congrès International de Mécanique des Sols et des Travaux de Fondations, Stockholm.

- LONG N.T., DELMAS Ph., POUGET P. (1984) - "Caractéristiques et domaines d'utilisation des pneumatiques usagés" - Bulletin de Liaison des Laboratoires des Ponts et Chaussées, n° 129.

- LONG N.T.(1984) - Le Pneusol" - Colloque "Routes et Développement" - E.N.P.C. , Paris, (Mai)

- LONG N.T. (1985) - "Le Pneusol ou l'art d'utiliser les restes" - Bulletin ISTED "Equipement et Développement", n° 16/17.

- LASSAUCE P., ANTOINE R., MIEUSSENS C., TESSONNEAU D., FEUTRIER D. (1984) - "Remblai en polystyrène dans l'Hérault", Revues générales des Routes et Aérodromes, n° 607 (Avril).

- LONG N.T. (1985) - "Le Pneusol : Réalisations" - Colloque "Innovations dans les techniques de la Route", Paris (Octobre 1985).

- LONG N.T. (1985) - "Le Pneusol" - Rapport des Laboratoires, n° 7 (Juillet 1985).

- LONG N.T. (1985) - "Les pneus en renforcement de terrains : Le Pneusol" - Le recyclage du caoutchouc et des matières plastiques - (Juin 1985), Journées ANRED.

- AUDEOUD B., LONG N.T., URSAT P. (1986) - "Pneusol, Tyresoil and the stabilization of slopes" - VIII Danube European Conference on Soils Mechanics and Foundations Engineering - Nuremberg (Sept.).

- GAIOTTINO C., LONG N.T., SALLE R., URSAT P.(1987) - "Le Pneusol et les Ouvrages de Soutènement" - IXème Conférence Régionale Africaine, Lagos (Septembre).

- DANTEC J., JEAN P.A., LONG N.T.,POUGET P., SAPYM. (1987) - "Le Pneusol et l'effet de voûte" - Colloque International "Interactions Sols-structures", Paris (Mai).

- LONG N.T. (1987) - "Domaines d'utilisation du Pneusol" - 4ème Colloque franco-polonais, Grenoble (Septembre).

- LAREAL P., LONG N.T., (1987) - "Le Pneusol réducteur de poussée" - 4ème Colloque franco-polonais, Grenoble (Septembre).

- DUVERNAY F., SOUPLY J.Y. (1987) : Etude du Pneusol réducteur de poussée - Rapport interne - INSA - Laboratoire Géotechnique (Juin)

- LONG N.T., MARCELLIER R., RAPIN R., URSAT P. (1987) - "Le Pneusol au CETE de l'Est - Bulletin Inforoute CETE Est .

- AUDEOUD B., LONG N.T., URSAT P. (1988) - "Une astuce à deux niveaux" - Revue des T.P.E. (Janvier/Février 1988).

- LEDOUX J.L., LONG N.T. - "Les réalisations du Pneusol - Info., 15 (Mars 1988) - CETE Sud-Est.

- BAILLY J.C., BESCOND B., GUILLARD Y., LONG N.T., SCHMUTZ D., URSAT P., VALEUX J.C., WASCHKOWSKI E. - "Le Pneusol : Recherches et Réalisations" - Congrès International de la Route de l'An 2000 (Septembre 1988), Berlin.

- LONG N.T. (1989), JEAN P.A., VAUTRIN J.C., URSAT P., WASKOWSKI E., BESCOND B., POUGET P., - Note d'information du SETRA.

- LONG N.T., VALEUX J.C., (1989) - "Le Pneusol Léger" - Rapport des Laboratoires GT n° 37, Novembre.

- JEAN P.A., LONG N.T. (1989) - "Creation of arching (Pneusol and other technics" - International Conference on - "Instrumentation in Geotechnical Engineering, Nottingham (April).

- LONG N.T., SCHMUTZ D., URSAT P. (1989) - "Lutzelhouse Landslide Repair Using Pneusol" - IIème International Symposium on Environmental geotecnicology, Tongji University, Shangai, China (May).

APPENDIX

OUVRAGES EN PNEUSOL

PNEUSOL STRUCTURES

1990

FRANCE

• OUVRAGES DE SOUTENEMENT - RETAINING STRUCTURES :
. Mur expérimental de Langres (1982) - Longueur : 10 m. - Hauteur : 5 m.
. Mur de Fertrupt (1984) - Longueur : 54 m. - Hauteur : 5 m.
. Mur de Meyzieu (1986) - Longueur : 25 m. - Hauteur : 5 m.
. Mur de Blandin (1986) - Longueur : 60 m. - Hauteur : 2 à 6 m.
. Mur du col de Bussang (1987) - (6 ouvrages) - Longueur totale : 650 m. - Hauteur : 2 à 7 m.
. Mur de Turckheim (1988) - Longueur : 100 m. - Hauteur : 2 m.
. Mur de Solaize (1989) - Longueur : 60 m. - Hauteur : 2 m
. Mur de Rothau (1990) - Longueur : "à m. - Hauteur : 5 m

• REDUCTEUR DE POUSSEE - REDUCE ACTIVE EARTH PRESSURE :
. Mur de Mende (1986) - Longueur : 54 m. - Hauteur : 5 m. - Epaisseur : 4 m.
. Mur de Munster (1988) - Longueur : 40 m. - Hauteur : 6 m. - Epaisseur : 3 m.
. Mur de Vendôme (1988) - Longueur : 20 m. - Hauteur : 5 m.
. Mur de la Fonderie (1988) - Longueur : 50 m. - Hauteur : 6 m.
. Piste olympique de Val d'Isère (+ buses) (1989) - (2 ouvrages) - Longueur : 200 m.- Hauteur : 6 m.
. Mur de Cernay (1990) - Longueur : 15 m. - Hauteur : 4 m.
. Mur de Sélestat (1990) - Longueur : 15 m. - Hauteur : 5 m.
. Boulsios (1990) - Longueur : 30 m. - Hauteur : 1,5 m (S.N.C.F.)

• RAIDISSEMENT DES PENTES - STIFFENING SLOPES :
. Route de Kruth-Marstein (1984) - Longueur : 80 m. - Hauteur : 4 m.
. Lutzelhouse RN 20 (1986) - Longueur : 30 m. - Hauteur : 6,5 m.
. Vierzon (1986) - Longueur : 80 m. - Hauteur : 3 m.
. Blois (1988) - Longueur : 15 m. - Hauteur : 7 m.
. Stand Oswald (1988) - Longueur : 10 m. - Hauteur : 4 m.
. CD 7 Petite Pierre (1988) - Longueur : 50 m. - Hauteur : 4 m.
. CD 130 Route du Strutof (1990) - Longueur : 25 m - Hauteur : 8 m

• ABSORBEURS D'ENERGIES - ENERGIE ABSORPTION :
. La Paravalanche de la Grave (1984) - Longueur : 120 m. - Epaisseur : 1 m.
. 2ème tranche (1986) - Longueur : 138 m. - Epaisseur : 1 m.
. Lambin La Terrasse (1988/89) - Protection d'un réservoir - Epaisseur : 2 m.
. Aigueblanche (+ géotextile) (1988/89) - Longueur : 850 m. - Hauteur : 7m,20
. Le Chant du Comte (+ géotextile) (1989) - Longueur : 400 m. - Hauteur : 4,50 m.
. Solaize (1989) - Longueur : 25 m. - Hauteur : 5 m. (S.N.C.F.)
. Lechère (+ géotextile) (1990) - Longueur : 600 m. - Hauteur : 6 m.

* **REMBLAI LEGER - LIGHT GROUND FILL :**
  . Cannes-Mandelieu , autoroute (1985) - Longueur : 80 m. - Hauteur : 3 m.
  . Tennis d'Altkirch (1986) - Surface : 800 m2 - Epaisseur : 1 m.
  . Glissement de Dommiers (1987/88) - Longueur : 50 m. - Epaisseur : 3,5 m.
  . Glissement de Crouttes (1988) - Longueur : 50 m. - Epaisseur : 3,5 m.
  . Piste de motocross - Romilly-sur-Seine (1989) - Longueur : 1.200 m. - Largeur : 4 m. - Epaisseur : 1 m.
  . Cannes Mandelieu RN 7 (1989) - Longueur : 100 m. - Hauteur : 3,5 m.
  . Boulsios (1990) - Longueur : 60 m. - Hauteur : 4 m. (S.N.C.F.)

PROTECTION DES BERGES ET DES PENTES - SAFETY DEVICE OF BANKS AND SLOPES :
  . Strasbourg (1986) - Longueur : 30 m. - Hauteur : 5 m. - Pente : - 2/3 -Surface : 250 m^2
  . Digue de l'Etang du Puits (1986/87) - Surface : 8.000 m2
  . Sucreries d'Artenay (1987) - Surface : 800 m2
  . Beaulieu-sur-Mer (1988) - Surface : 600 m2 (S.N.C.F.)
  . Langres, canal Saône-Marne (1988) (3 ouvrages) - Longueur : 400 m.
  . Le Bruckenbach (1989) - Longueur : 10 . - Largeur : 5 m.
  . Enrochement du Pont St-Michel à Blois (1989)
  . Langres, canal Saône-Marne (1990) - Longueur : 500 m. - Hauteur : 1 m.
  . Langres (1990) - Longueur : 2.000 m. - Hauteur : 1 m.

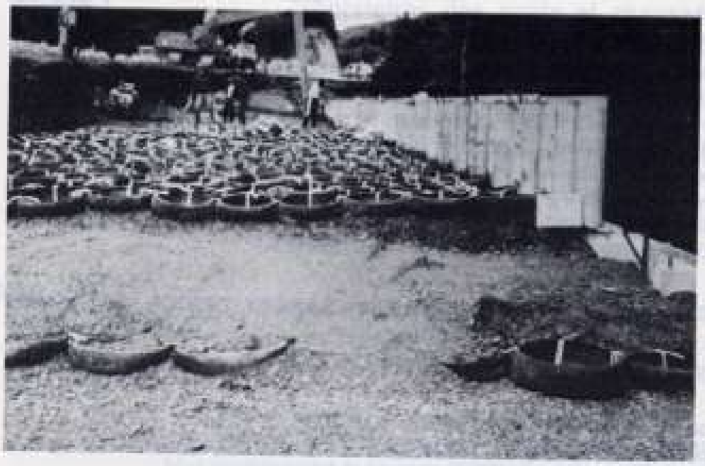
* **REPARTITEUR DE CONTRAINTES - CREATION OF ARCHING :**
  . Monistrol-sur-Loire (1985) - Longueur : 140 m. - Epaisseur : 2 m.
  . Franchissement du Banacho (1985) - Longueur : 140 m. - Epaisseur : 2 m.
  . Pont de Sayat (1986) - Longueur : 100 m. - Epaisseur : 2 m.
  . Le Marqueran (1987/88) - Longueur : 54 m. - Epaisseur : 2,5 m.
  . Xertigny (1987) - Longueur : 58 m. - Epaisseur : 2 m.
  . Bruckenbach (1988) - Longueur : 55 m. - Epaisseur : 2 m.
  . St-Paul de Le Ménard (1988) (5 ouvrages) - Longueur : 60 m. à 80 m. - Epaisseur : 0,30 m. à 0,60 m.
  . Autoroute A 47 (1988/1989), contournement de St-Chamond - Longueur : 110 m. - Hauteur : 1,20 m.
  . Mouans-Sartoux (1988/89) - Longueur totale : 300 m. - Epaisseur : 2 m.
  . St-Chely d'Apcher RN 9 (1990) - Longueur : 120 m. - Epaisseur : 2 m.
  . St-Chely d'Apcher RN 9 (1990) - Longueur : 90 m. - Epaisseur : 1,5 m.
  . RN 20 Croisières (1990) (2 ouvrages) - Longueur : 70 m. - Epaisseur : 2 m.
  . Contournement de Béziers (1990) - Longueur : 80 m. - Epaisseur : 2 m.

* **PNEUSOL MILITAIRE - MILITARY APPLICATIONS :**
  . Rampe pour VAB (1987) - nombre : 2

* **OUVRAGES SPECIAUX - SPECIAL STRUCTURE :**
  . Les Colonnes de Bourges (1987/88)

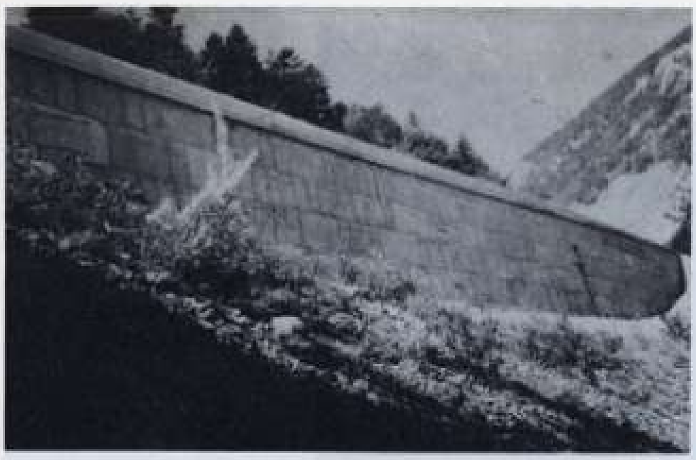
E t r a n g e r - foreign countries

* **REPARTITEUR DE CONTRAINTES - CREATION OF ARCHING :**
  . Aïn Témouchent (Algeria) (1986) = 12 ouvrages



Establishing Pneusol

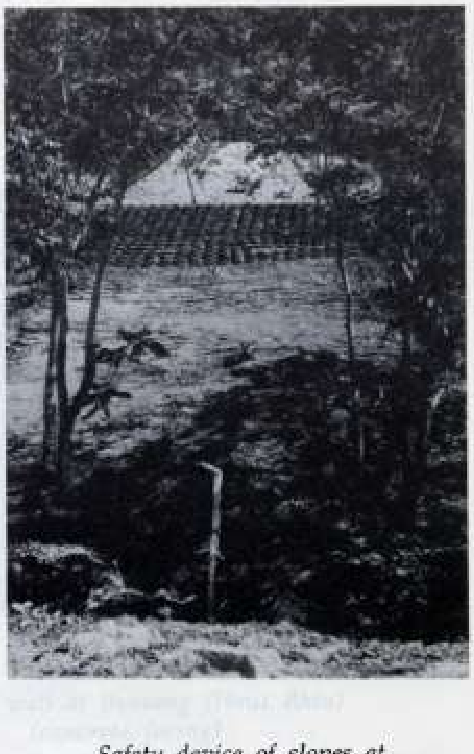
Pneusol wall at Bussang (Haut Rhin) (concrete facing)



Pneusol wall at Bussang (Haut Rhin)
(concrete facing)

Fertrupt wall (Haut Rhin)
(concrete facing)

Pneusol wall at Bussang (Haut Rhin)
(Pneusol facing)



Safety device of slopes at
Beaulieu-sur-Mer (Alpes Maritimes)

Safety device of banks at Puits pond (Cher)

Creation of arching
at Monistrol-sur-Loire (Haute Loire)

Energy absorption at La Grave

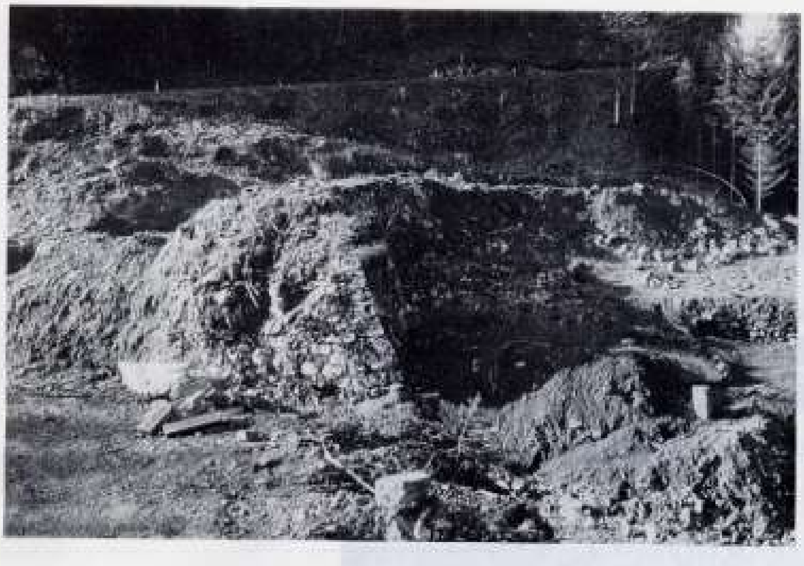
Light ground fill at Cannes Mandelieu
(Alpes Maritimes)

Reduce active earth pressure at Mende (Lozère)

Military applications

Energy absorption at Aigueblanche (Pneusol facings - Reinforcements with geotextiles) (Savoie)

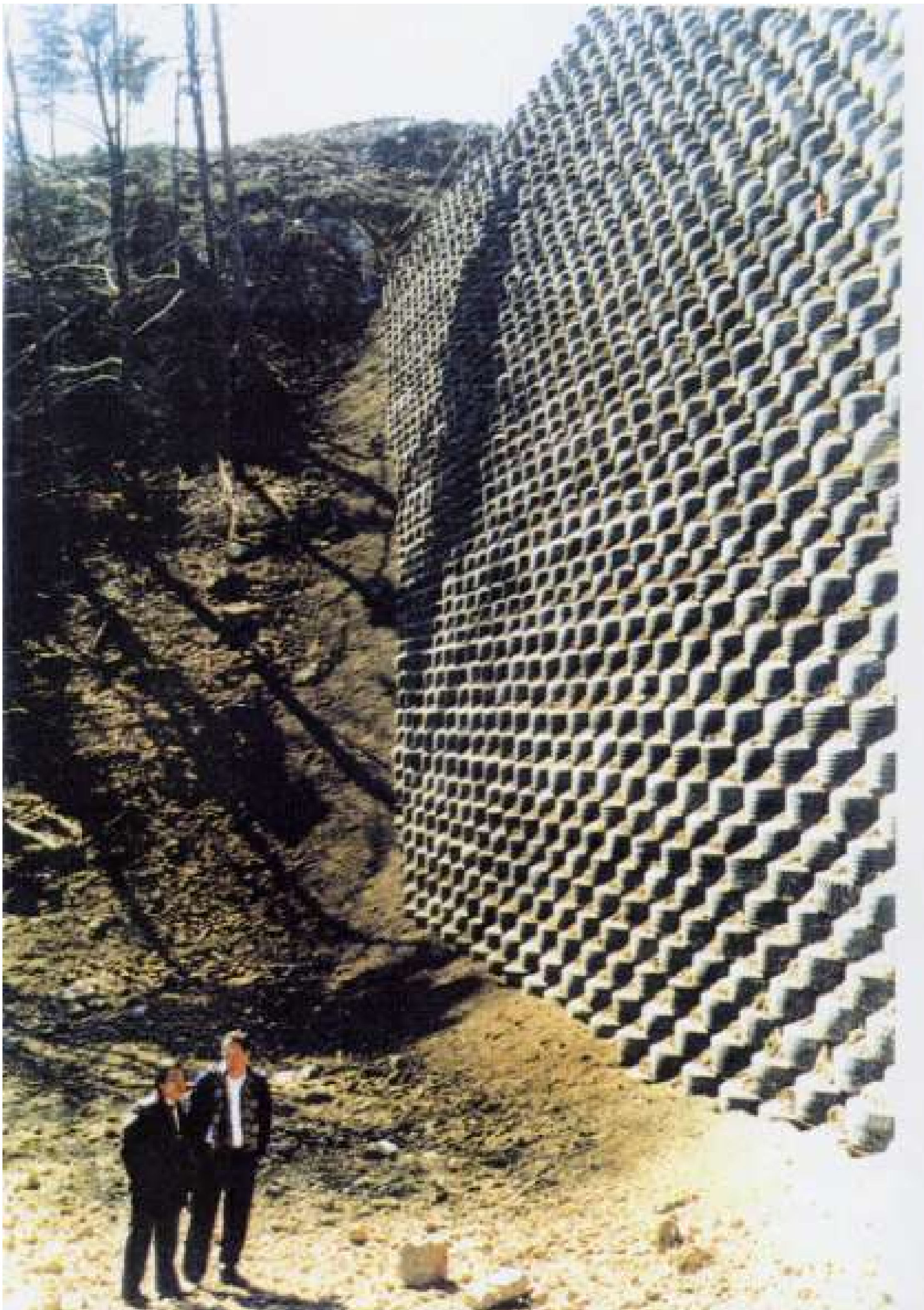
Pneusol and Geotextiles again differential settlement
Cannes Mandelieu (Alpes Maritimes)



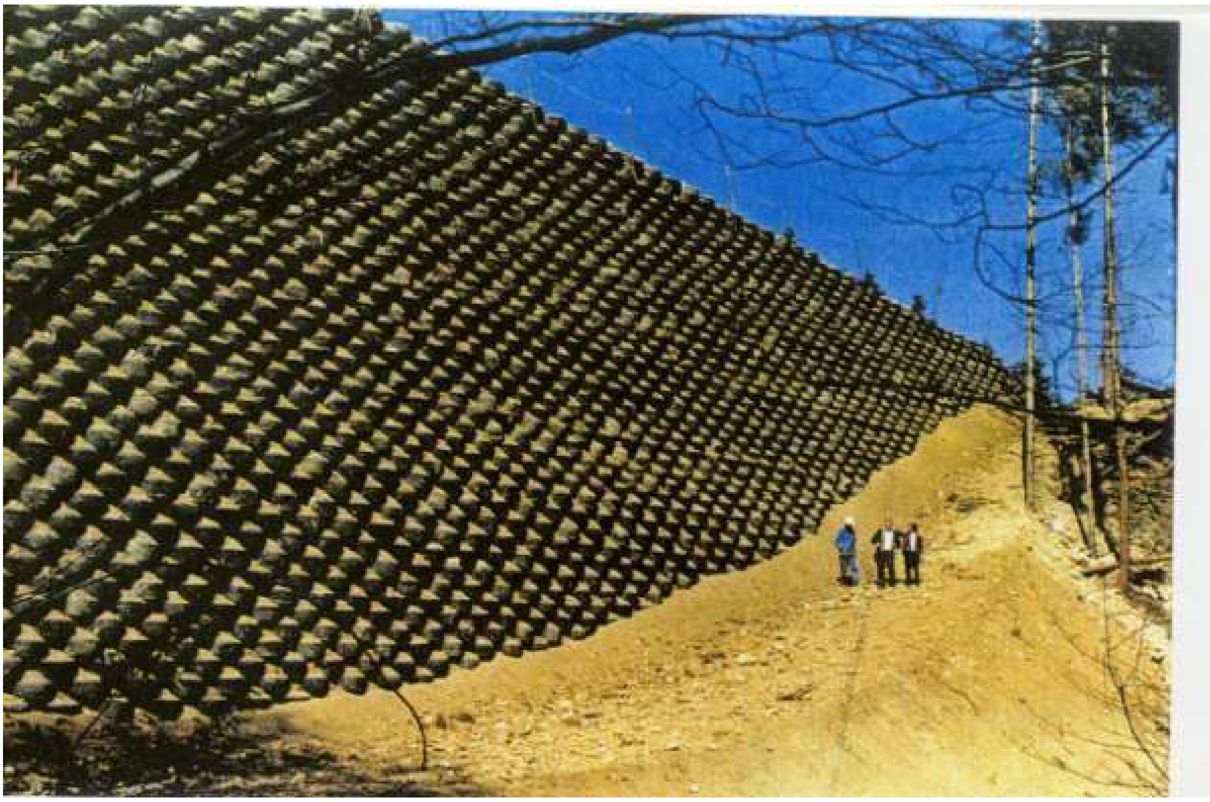
Reduce active earth pressure
at Bussang (Haut-Rhin) (behind a wall)

Bearing capacity tests
(LRPC Melun)

Publié par le LCPC, 58, bd Lefebvre - 75732 Paris Cedex 15 sous le numéro 3586
Dépôt légal : décembre 1990
ISBN : 2-7208-3586-2



ARMAPNEUSOL : patented by LCPC and Foréziennes C° is composed with Pneusol facing and metallic grid reinforcemnts



ARMAPNEUSOL