A LEAD FOR WATER RESOURCES PRESERVATION IN EARTHWORKS PROJECTS

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RÉSUMÉ

Water consumption in earthworks can be an important economical and environmental issue for projects realised in some specific geological and climatic contexts. The question is, in particular, to assess the risk of using dry or arid soils, which long-term behaviour remains uncertain. Recent site observations and research results are leading to distinguish two problems : the difficult compaction of dry soils and their long-term behaviour, in particular due to wetting.

The answers that are brought in this paper indicate that, even if it needs intense energy, compaction of dry soils can lead to sufficiently high compaction rate to avoid wetting-induced settlements for low to moderate plasticity soils. This gives arguments for a design of road and railways embankments built with dry and arid soils, but also points out the high necessity of intense compaction control.

1. INTRODUCTION

In earthworks, economical stakes are generally related to extraction, removal of loose materials, soils stabilization, volumes of granular materials ... Nevertheless, when materials available in the project reservation are dry or even arid, watering can be necessary, leading to take water in rivers or aquifers and transferring it to the works site. In draught periods and, more generally, in countries where water is scarce, such a practice can be economically and environmentally unacceptable. Being able to use these dry soils without water addition then becomes a major stake.

In this paper are presented the stakes and limitations of the current practice concerning the use of dry soils and experimental results which could lead to enlarge the use of these materials in embankments without water addition. These results will be used to identify the basic ideas for a safe dry soils embankments design.

2. CURRENT PRACTICE LIMITATIONS

The fact that embankments constituted by fined-frained soils are likely to present deformations (swelling and/or settlement) is known for a long time. In the whole, disorders are all the more important since materials are sensitive to water, compaction rate are unsufficients, embankments height is important and design doesn't prevent from water circulation in the embankment, either by the platform or the slopes or the base (Auriol *et al.*, 2000).

Materials use rules vary around the world depending on countries habits and local specificities but they all take into account this knowledge on fine-grained soils embankments behaviour. As an example, in France, the guidelines (SETRA-LCPC, 2000) detail these conditions depending on :

- soils nature (grain size distribution, plasticity,…) ;
- soils hydric state, defined on the basis of compaction optimum or bearing capacity;
- the stress applied to the soil, i.e. embankments height.

The subsequent compaction conditions are supposed to lead to an average compaction rate of 95 % higher than 92 % in the base of elementary compaction layers.

Because of the supposed influence of the initial hydric state on wetting-induced behaviour and given that compaction of very dry soils is difficult, the use of such materials is not allowed according to the French guidelines (SETRA-LCPC, 2000). They can be used only if a watering can lead to a water content higher than 70 % of the optimum Proctor moisture content (OMC).

An extension of these specifications for very dry to arid soils has been suggested by Morel et al. (2002) and integrated in the english version of the guidelines (LCPC, 2003). Nevertheless, these extended specifications limit the use of very dry soils to embankments lower than 3 meters. The authors have considered that, without specific quantitative studies, it was not possible to prove that long-term wetting won't lead to settlement or swelling, even if compaction rate objectives are respected.

Thus, the usual rules allow to use very dry soils without watering only in very limited conditions (embankments height in particular). For higher embankments, watering can lead to three kind of impacts :

- Economical over-costs : in some contexts (in particular in arid areas), each liter of water can reach a value of one euro; Hence, if it is necessary to increase the water content of 4 points (for example), the total volume of water needed for a 100000 cubic meters embankment would be of 8000 cubic meters for a cost of 8 millions of euros. It means that this solution is not economically relevant ;
- Environmental impacts : a 250 km motorway project concerned by the use of very dry soils can lead to consume tens to hundreds of thousands of cubic meters, which can have consequences on the local water resources ;
- Social aspects : such volumes of water correspond to the domestic consumption of water of a city of 10000 people in the south of Morroca, for example and their use for earthworks is, from this point of view, inadequate.

3. TECHNICAL ANALYSIS AND SITE EXPERIENCES

Dry materials can be met almost in all countries and, given the expected climate change evolution, probably in an increasing manner. The most common contexts are as follows :

- in dry to arid climate countries, the low water content is the consequence of the very low air relative humidity and the high air temperature. This case often concerns dunes sands (Cissé, 1980, Cheikh *et al.*, 1995, Ben Dhia, 1998), which, besides their low water content, are characterized by an homometric grain size distribution leading to compaction and works traffic difficulties ;

- The second case concerns evolutive rocks such as pelites (Bernhard *et al.*, 2007) and, more generally, clayey rocks. Due to their high level of consolidation, the water content of these materials is low compared to the optimum Proctor water content of the soils obtained after extraction (Figure 1).

An important point is that all these dry materials are very sensitive to wind erosion (Figure 2) and they are characterized by relatively high values of suction, which increases the risk of long-term wetting. Hence, settlements and bearing capacity losses must be considered with high attention.

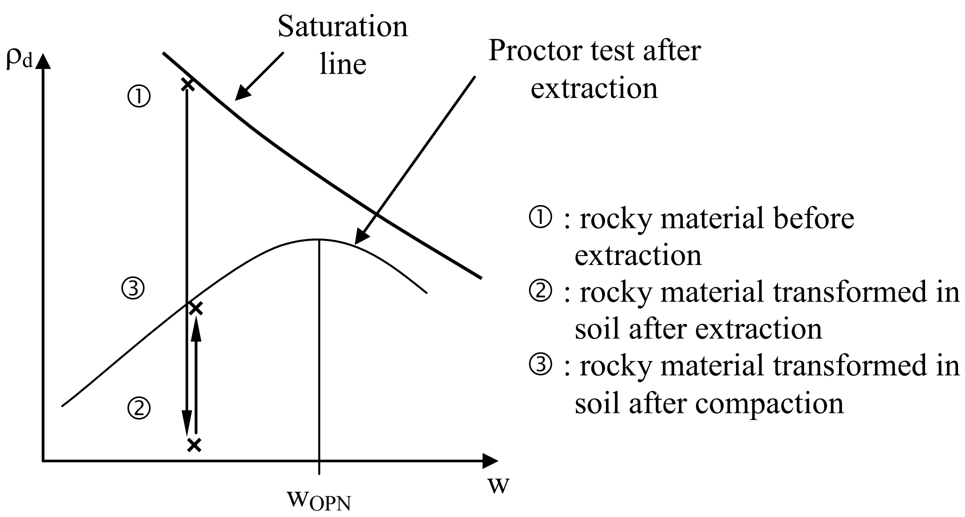

Figure 1. Evolution of a rocky material in the Proctor diagram during the extraction and compaction process.

Figure 2. Use of very dry mica schists on a motorway works site in the Marrakech area (Morroco).

Research and methodologies development have been led on dry to arid soils (ISTED, 1987, Morel *et al.*, 2002) which underlined the singular shape of the Proctor curve for very low water contents (Figure 4). As a matter of fact, the decrease of water content leads to a dry density decrease only above a given value of water content, called “critical water content” (w_c), where dry density reaches a minimum value. This minimum corresponds to a low compaction rate (often lower than 85 %). Hence, for dry to very dry soils, an acceptable compaction rate can be obtained only with a very high compaction energy. For example, for a low plasticity fine-grained soil (more than 35 % of fines, plasticity index lower than 12), in a dry hydric state, the guidelines (LCPC, 2003) impose to compact the material in 35 centimeters thick layers, with at least 8 passes of compactor at a speed of 2,5 km/h. For a same layer thickness and the same compactor, but at the Proctor optimum water content, the compaction can be done with only 3 passes at 4 km/h. Thus, because of the dry state of the soil, the compaction productivity is divided by 4.

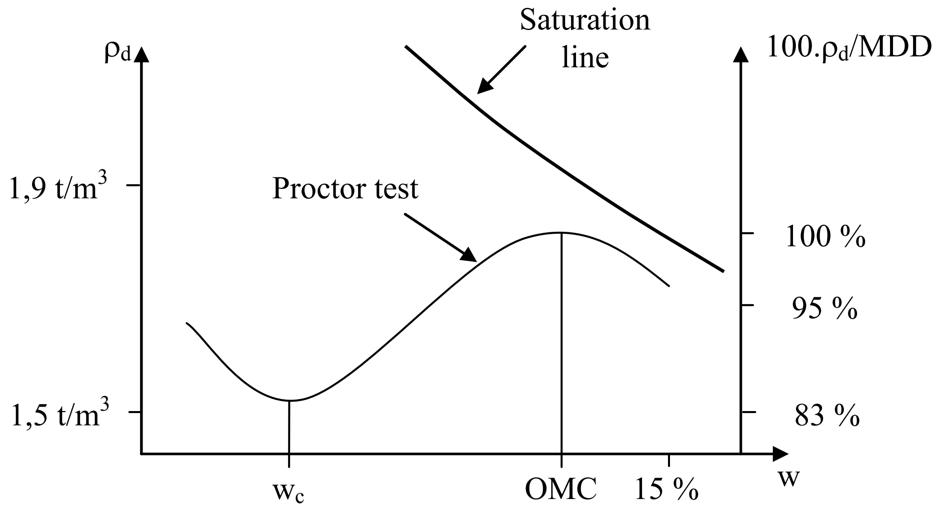

Figure 3. Typical Proctor test at very low water content (after ISTED, 1987)

In spite of these difficulties, recent experiences led in France (Figure 4, Bernhard *et al.* 2007) and in Morroco showed that an average compaction rate of 95 % could be obtained with dry or very dry clayey rocky materials.

Thus, compaction is one of the problems presented by dry soils but it is often possible to reach the compaction objectives expected in embankments. The question is then how to evaluate the risk caused by the long-term evolution. This is the goal of the following part, which deals with the wetting-induced consequences in fine-grained low plasticity soils.

Figure 4. Compaction of a very dry pelites.

4. WETTING-INDUCED BEHAVIOUR OF DRY SOILS

In road geotechnics, saturation is often considered as the worse stress. This idea is used in road design, in particular by using the California Bearing Ratio after immersion. For embankments bodies, the bearing ratio is not as important as settlements generated by the saturation under stress due to the weight of the embankment itself.

In order to study this question and quantify possible deformations, series of inundation tests have been performed on a moderate plasticity silt of the Normandy region (NW of France - Table I). The classification of the soil is A2 according the french standard (AFNOR NF P 11 300) and Ap in the USCS classification.

Table I. Caractéristiques géotechnique du limon de Goderville.

w_L (%)	I_P	$C_{2\mu m}$ (%)	ρ_s (Mg/m^3)	Std OMC (%)	Std MDD (Mg/m^3)	Methylene blue value (g/100 g)	CEC (cmol+/kg)
41,2	19,3	35	2,67	17	1,75	3,48	12,5

The tests consisted in compacting soils samples in oedometric cells at different dry densities and at two different water content : a water content close to the optimum Moisture content (18,1 %) and a water content corresponding to the dry hydric state (13,4 %). Samples were loaded under a given vertical stress and, after stabilization under this stress, saturated. The measurements consisted in determining :

- the void ratio after compaction or initial void ratio, corresponding to the void ratio which would be measured after the compactor work ;
- the void ratio after loading, which corresponds to the void ratio of the material at the end of the embankment construction, generated by the increase of vertical stress ;

- the void ratio after inundation or final void ratio, which would correspond to the soil state after years life in the embankment.

Under a given vertical stress, 100 kPa for example, which corresponds to an embankment height of approximately 5 meters, the plot of the final void ratio after plotted against the initial void ratio (Figure 5) shows that :

- when samples are "well-compacted", i.e. for low void ratios, settlements due to inundation are low or even negligible, whereas loosely compacted samples shows non negligible settlements, all the more high since the initial void ratio was high ;
- under a given vertical stress, the final state of this silt only depends on initial void ratio and absolutely not on the initial water content. This surprising observation has been confirmed on other low plasticity fine-grained soils ;
- for loosely compacted samples, the settlement due to inundation leads to a given void ratio, which depends neither on the initial void ratio nor on the initial water content.

These results confirm the importance of compaction, since a low value of void ratio (or a high value of dry density) enables to avoid wetting-induced settlements. On the other hand, the influence of initial water content seems to be negligible in this part of the soil behaviour, which suggests that water content is maybe not a problem in itself, provided that a sufficient dry density is obtained.

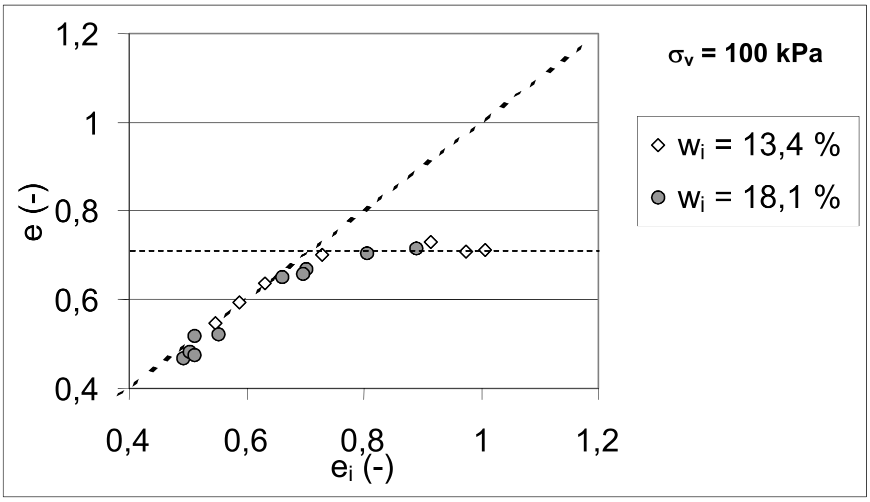

Figure 5. Influence of initial water content and void ratio on void ratio after inundation of a compacted silt.

These experiments were also performed on other vertical stresses (Figure 6) and this phenomenon was observed for all the vertical stresses higher than 100 kPa. It can be seen that the void ratio after wetting-induced settlement of loosely compacted samples decreases when vertical stress increases. In other words, the higher the embankments high, the higher the dry density that must be obtained to prevent from wetting-induced settlements.

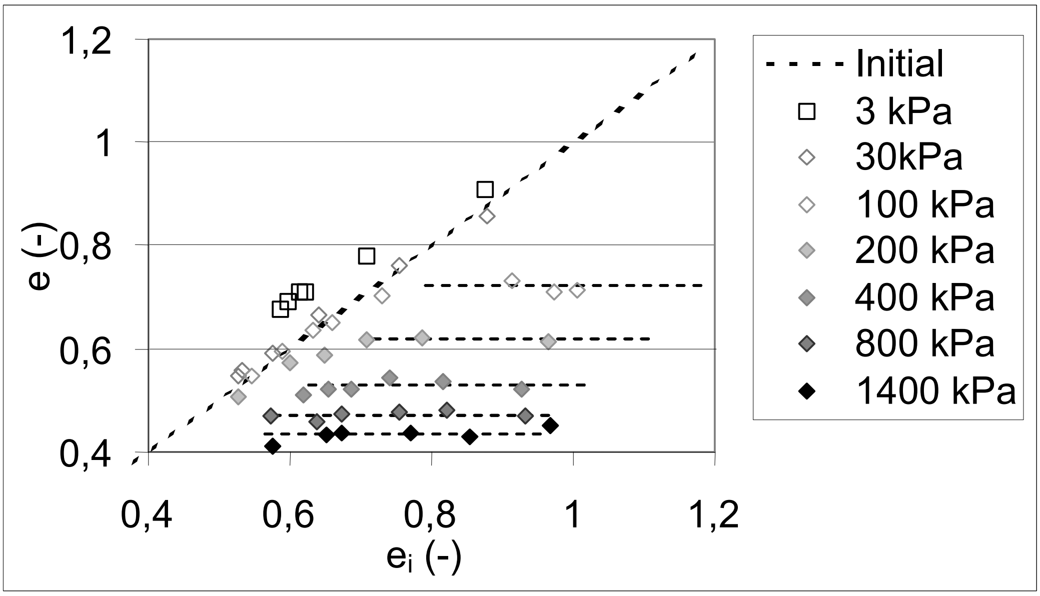

Figure 6. Influence of initial void ratio and vertical stress on void ratio after inundation.

Moreover, it appears that the influence of vertical stress on void ratio after inundation follows a semi-logarithmic law (Figure 7) which corresponds precisely with the oedometric compression curve obtained on an initially loosely compacted sample. Hence, such an oedometric test could enable to define the compaction objectives regarding the embankment height.

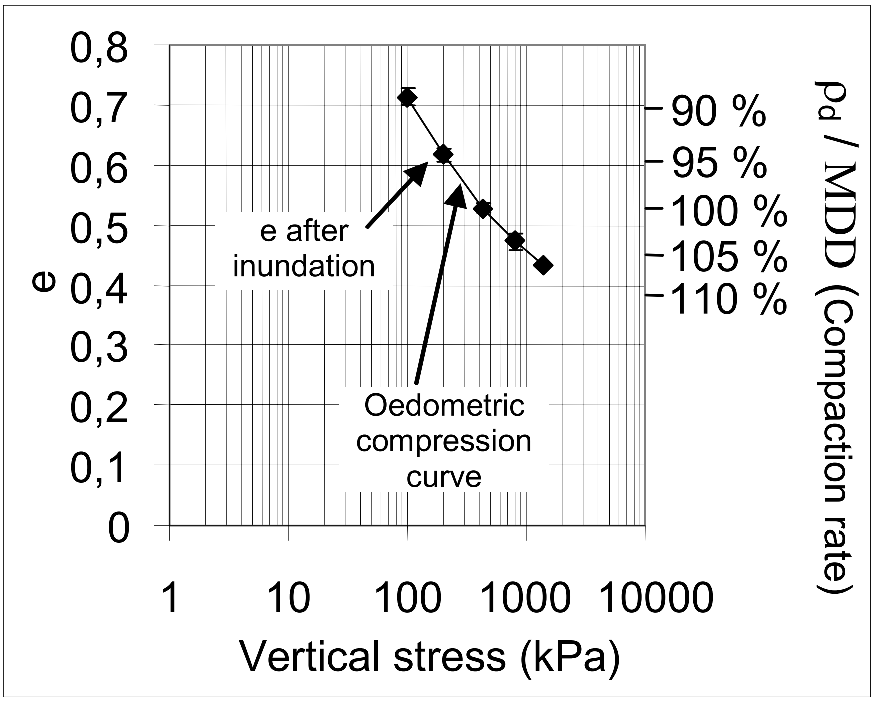

Figure 7. Influence de la contrainte verticale sur l'indice des vides après tassement par inondation.

Such series of tests were performed on other low to moderate plasticity soils and it was observed that the compaction rate objective for a 10 to 15 meters embankments height should be approximately 95 % (Figure 8) and that this objective should increase to more than 100 % for embankments higher than 20-25 meters.

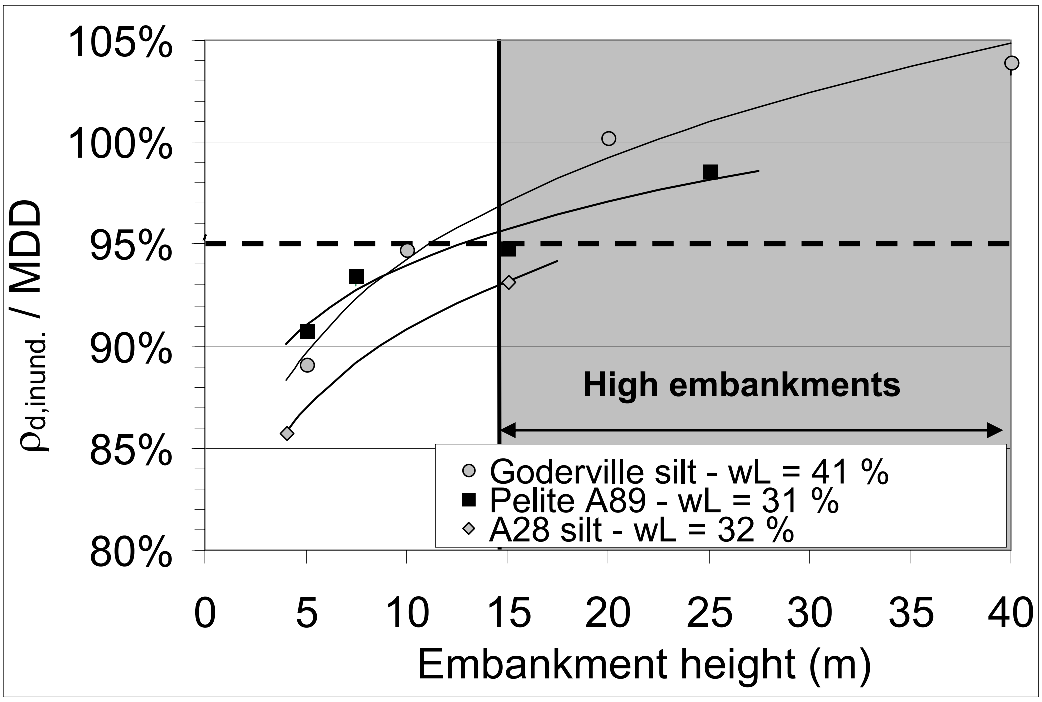

Figure 8. Influence of embankments height on compaction rate objectives according to inundation tests results on three soils.

These results constitute a scientific base to previous site observations and to the current habits in embankments design (Puech, 1989), which had already highlighted the necessity to adapt compaction rate to embankments height (Figure 9).

Thus, the compaction is not good or bad ; a soil is sufficiently compacted or not depending on the embankment height. Nevertheless, it is also very important to mention that this remark is only relevant for the question of wetting-induced deformations in the bases of embankments and that compaction is also necessary to lower permeability, to ensure a good homogenization of dry density and to obtain the mechanical strength which are necessary conditions for a long-term stability of embankments.

Finally, it must also be noted that this wetting-induced behaviour is basically different and more complex in the case of high plasticity clays (plasticity index higher than 25-30; Ferber, 2006), for which a stabilization is often required and a use at low water content would constitute an uncontrolled risk.

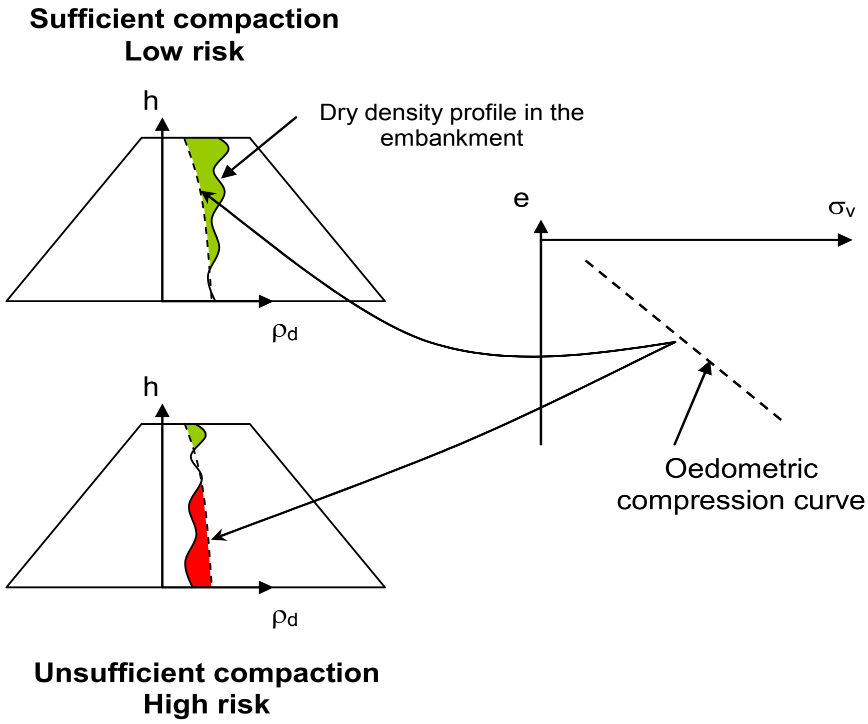

Figure 9. Principle of the compaction rate objective method.

5. CONSEQUENCES ON DRY SOILS EMBANKMENTS DESIGN

As indicated in the « Problematic » part, the use of dry to arid soils can be a major economical or environmental issue in some sensitive contexts. The experiences and experimental results presented above give the opportunity to suggest a realistic approach on the basis of the following observations :

- even though dry and arid soils compaction is an energy consuming process, it is generally possible to obtain compaction rate of approximately 95 % with modern compaction plants ;
- in low to medium height embankments, namely lower than 10-15 meters, the consequences of wetting depend mainly on the initial compaction rate. It has been shown that, whatever is the initial water content, if the soil is compacted beyond a compaction rate of 95 %, wetting-induced deformations are negligible for low to moderate plasticity fine-grained soils.

Consequently, it can be considered as reasonable to use such dry or arid soils without adding water if the embankment height is limited to 10-15 meters and if the compaction process leads to a dry density higher than 95 % of the maximum dry density.

Two other points must be taken into account in the design of dry soils embankments :

- dry soils are notoriously highly sensitive to wind or water erosion ;
- the long-term bearing capacity of the highest layers of the embankments can probably not be ensured if materials are dry, because of the mechanical properties losses which would occur in case of wetting.

Consequently, the design of dry soils embankments must be based on a structure (Figure 10) which consists in :

- using non-sensitive materials in the upper part of the embankment, in order to ensure sufficient long-term bearing capacity under the capping layer and road structures ;
- using materials non sensitive to erosion, namely granular materials with a maximum diameter of particles larger than 63 mm ;
- building the embankment body with the available dry soils, while taking into account the embankment height in the definition of the compaction rate objective.

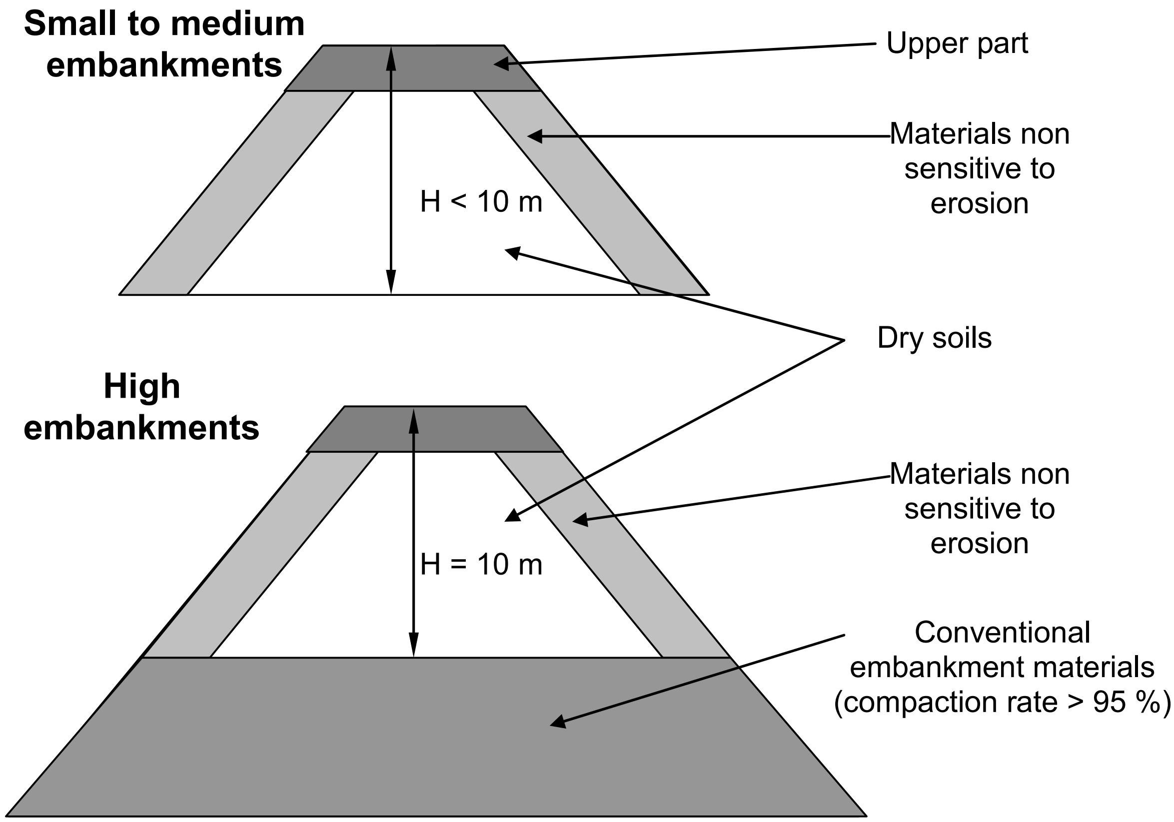

Figure 10. Example of dry soils embankment design.

To this design must be added a control plan which includes very strict compaction rate controls, in order to avoid high compaction layers thicknesses and to verify that the compaction rate is obtained. Hence, the control plan should not be limited to the use of a global method (the French Q/S method for example), but should also include local dry density measurements. Unfortunately, this control could be difficult for very coarse materials, because of the poor representativeness of both the compaction test and the dry density measurements.

6. CONCLUSIONS

The use of dry to arid soils in embankments is not a recent issue but, due to the increase of both economical and environmental concerns, it has become a crucial question in some projects. The preservation of water resources and the need to limit economical expenses lead owners and project managers to try to use such materials in roads embankments. It seems to be necessary to support this trend with new information on dry soils behaviour and a specific approach.

For that, inundation tests were performed on compacted soils in order to study the influence of initial water content and dry density on wetting-induced deformations. It appeared that, for low to moderate plasticity fine-grained soils, compaction rate is the main influential parameter, since a sufficient compaction rate prevents from settlements due to wetting. The results show that the objective of compaction rate must depend on the embankment height and that the current specifications (compaction rate higher than 95 %) should prevent from settlements in embankments lower than 10-15 meters.

Experiences of works realised with such dry soils have shown that this compaction rate objective can be reached, provided that sufficient compaction energy is applied. This leads the authors to say that using dry or very dry soils in embankments can be admitted, even in embankments higher than 3 meters, but this must include an adapted design of embankment and a very strict control plan during construction.

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