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Column Supported Embankments for Transportation Infrastructures: Influence of Column Stiffness, Consolidation Effects and Cyclic Loading

Remblais sur sols renforcés avec de colonnes ballastées pour les infrastructures de transport: Influence de la rigidité des colonnes, des effets de consolidation et du chargement cyclique

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ABSTRACT: Ground improvement methods based on column-type elements are analyzed regarding the influence of the column properties on serviceability and safety of the Column Supported Embankments (CSE). Particularly, treatments made by rigid inclusions are analyzed and compared with stone columns. Stiffness of column-type elements determines the design and risks involved. Rigid inclusions are analyzed according to the recent French national project ASIRI. In the case of these elements, a considerable mobilization of negative skin friction and punching effects governs their behavior in the Ultimate Limit State, which represents a non-ductile mechanism of failure. Whereas stone columns present a ductile behavior determined in the domain of Serviceability Limit State (SLS). It is pointed out, that possible damages on CSE systems may extend settlement stabilization due to the consolidation process, if no drainage elements are adopted. It is also noted that risks related to rigid columns in the SLS under cyclic loading, may be decisive in the design of CSE composed by low-heights embankments. Briefly, it could be stated that rigid inclusions present higher risks, increasingly when their diameters are smaller than 30 cm.

RÉSUMÉ : On analyse les méthodes d'amélioration des sols avec des colonnes pour la fondation des remblais sur sols mous. En particulier, on analyse les inclusions rigides selon les recommandations du récent projet national français ASIRI, et on présente la comparaison avec des colonnes ballastées. La rigidité de la colonne détermine la conception et les risques associés. Dans le cas des inclusions rigides, une mobilisation considérable du frottement négatif et la portance résultante gouvernent leur comportement dans l'état limite ultime, ce qui représente un mécanisme non-ductile de rupture. Au contraire, les colonnes ballastées présentent un comportement ductile déterminée dans le domaine de l'état limite de service. Il a été observé que les risques de colonnes rigides dans les ELS peut être retardés à moins que on installe quelques éléments de drainage. On a remarqué aussi que les risques associés aux inclusions rigides soumises aux chargements cycliques peuvent être décisives pour remblais de faible hauteur. Ainsi, les inclusions rigides présentent des risques plus élevés, de plus en plus lorsque leur diamètre est plus petit que 30 cm.

KEYWORDS: Load Transfer Platform, geosynthetic, embankment, rigid inclusion, stone columns, risk, stiffness, arching effect

1 INTRODUCTION

Column Supported Embankments (CSE) represent an innovative solution for transport infrastructure over soft soils, in order to reduce execution time and general earthworks. Hence, the use of low-height embankments based on column-type elements tends to be preferred, whenever possible, instead of direct soil replacement or preloading with or without vertical drains. Recently, the use of CSE is increasing, and consequently growing interest in developing reliable and unified criteria for their design and construction is observed.

However, due to the possibility of application of a wide range of ground improvement techniques, further risk assessment has to be done. Risks and reliability related to CSE could be largely analyzed considering the influence of column stiffness in Ultimate and Serviceability Limit States. Furthermore, column stiffness also affects consolidation process and the system behavior against cyclic or dynamic loading, very often decisive for safety and serviceability.

2 COLUMNS SUPPORTED EMBANKMENT SYSTEMS

2.1 *Type of columns*

Typical elements of CSE systems are shown in Figure 1. Initially, reinforced piles with concrete cap were applied, in order to absorb the largest load of embankment as possible. In order to optimize the solution, ground improvement methods have been increasingly used in the last years.

Ground improvement methods should intent not to take the entire action by the supporting elements, but only the difference between the required and existing bearing capacity without improvement (Wehr et al. 2012). This is applicable to stone and sand columns, which take important part of the foundation load, and make the most of soil confinement to ensure its own capacity. These two types of columns accelerate the consolidation process and do not need any embedment to transfer the loads to stiffer soil layers; thereby they can be considered as authentic ground improvements.

On the other side, the columns made by the addition of bonding agents, mortar or concrete into the ground, do not accelerate consolidation. The improvement introduced by such columns mainly consists of the load transfer to the stiffer layers in the same way as piles, thus, to ensure their correct application the largest embedment is frequently desired.

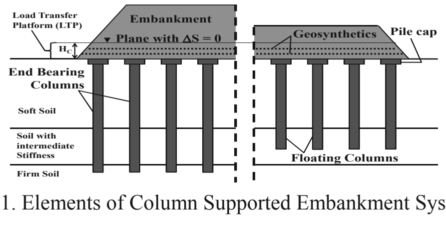


Figure 1. Elements of Column Supported Embankment Systems

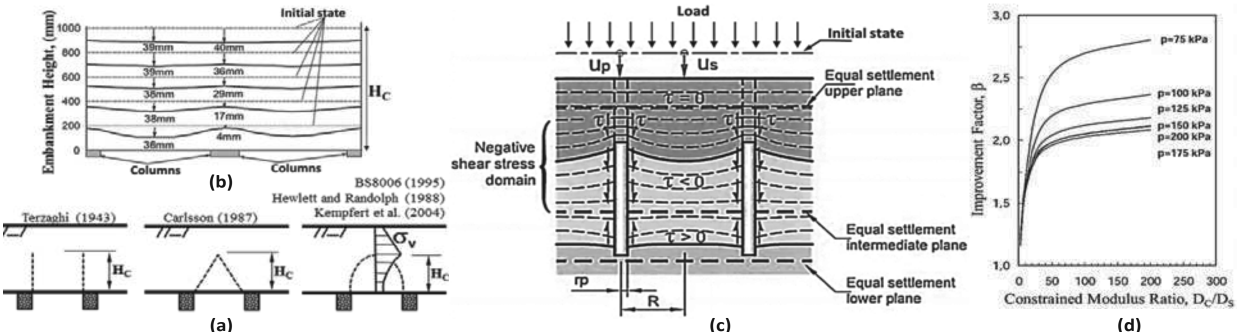


Figure 2. Mechanism of load transfer in the CSE: (a) approaches of arching-effect shape; (b) resultsof laboratory test performed by Chen et al. (2008); (c) load transfer mechanism proposed by Combarieu (1974, 1988); (d) influence of confined modulus on improvement factor (Kirsch 2004).

These kinds of columns, with predominantly round cross-sections of 25 cm to 80 cm diameter, are denominated Rigid Inclusion according to the French national research project ASIRI (Améliorations de Sols par Inclusions Rigides). Rigid inclusions may be arranged in a regular grid, although, due to horizontal stresses sometimes have to be distributed in wall or panel form in order to overcome slope and internal instability.

2.2 *Load Transfer Platform*

The design and operation of CSE is largely influenced by the load transmission mechanism toward the columns, through a Load Transfer Platform (LTP) laid out at the base of embankment. LTPs are generally composed by a layer of compacted granular material that in many cases has to be reinforced by geosynthetics, or composed by layers treated with hydraulic binder.

LTP behavior is essentially determined by two parameters. The efficacy or efficiency E, defined as the ratio between load on the column head Q_P and the total load on the surrounding soil within a unit cell (W + Q), where W is the weight of embankment and Q is the force due to surcharge on the surface; and the critical Height H_C, which indicates the height of embankment where differential settlements in between column head and middle of the grid are negligible. As stated by several authors, E and H_C depend on many factors such as column rigidity, shear strength of LTP layers, spacing between columns, and soft soil stiffness (Zaeske and Kempfert 2001, Okay 2010).

Most theoretical methods focus on the requirements of the geosynthetic within LTPs for piled embankments, considering a void between rigid elements. The geosynthetic takes the load that remains in the middle of columns and delivers it to the column heads by means of membrane effect. Consequently almost all load is acting on the columns heads. According to these methods only a minor part or even any soil reaction is considered. Several guidelines or recommendations documents deal with these methods (BS8006 2010, EBGEO 2010, Nordic Handbook 2005). Such approaches could be classified according to the shear stress form-distribution that governs the mechanism of arch load-transfer and differential settlements within the LTP (Han and Colling 2005), see Figure 2a. According mentioned approaches H_C varies from 0.7 to 1.6 times the clear distances between columns (s - a).

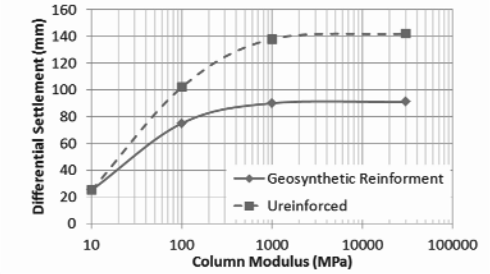


Figure 3. Influence of column modulus on the differential settlements within Load Transfer Platform (Gangakhedar 2004).

Otherwise, the method proposed by Combarieu (1974, 1988), and adopted in the ASIRI Recommendations, deals not only with the load transfer into LTP but also along the entire length of rigid columns. Furthermore, ASIRI project's recommendations are based on various physical and numerical modelling (Jenck 2005, Chevalier et al. 2008). 1º

Figure 2c shows the mechanism of load transfer proposed in the ASIRI, where differential settlements between soil and columns produce negative skin friction in the upper part of the column; at certain depth where settlements are the same in soil and columns, the skin friction is equal to zero, and below this neutral plane the load in the columns is transferred through positive skin friction and tip resistance. It can be noted that such mechanism is quite similar to those exhibited by the combined pile-raft foundations (CPRF).

3 INFLUENCE OF THE COLUMN CHARACTERISTICS

3.1 *Columns stiffness*

Unfortunately, so far there is not any analytical method (commonly used) that takes into account the variation of column stiffness, and accordingly numerical modelling usually have to be performed to analyze the influence of column stiffness. However, even the most relevant numerical modelling that can be found in the literature has no focus on the risks and suitability aspects related to the column stiffness.

Kirsch (2004) analyzed the influence of the ratio between confined modulus of columns and soil on the improvement factor β (ratio of settlements with and without improvement). Results indicate that confined modulus ratios beyond 40 to 50 do no suppose considerable increments on improvement factor β, (Figure 2d). Similarly, Gangakhedar (2004) performed a numerical analysis of the influence of Young's modulus of the columns, on the differential settlements at the base of geosynthetic reinforced embankment. Figure 3 shows that differential settlements increase with increasing column modulus. Although it can be noted that there exists a greater increase of differential settlements when modulis are higher than those usually obtained for stone columns, of about 80 to 120 MPa, and that differential settlements tends to be much higher with the increase of column modulis if no geosynthetic reinforcement is considered.

Therefore, the cost-operating inefficiency of columns may be stated when column modulus are higher than 120 MPa, or modulus ratio are larger than 40 to 50, approximately. If columns rigidity exceeds this limits, CSE system requires an increase on the capacity of geosynthetic-reinforcement and the additional improvement is negligible.

It is well known that stone columns have a load-carrying mechanism by lateral bulging, whereas rigid inclusions transmit the load by skin friction and punching effect on their tip and head. In the latter case, the usual amount of differential settlement obtained in the column head implies a behavior controlled by its ultimate limit state (ULS), and governed by mobilization of negative skin friction. Figure 3 depicts that such

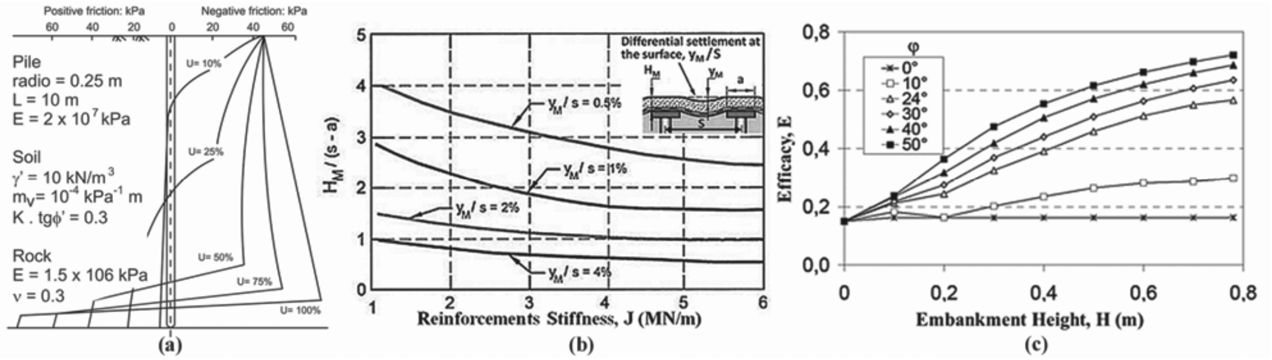


Figure 4. (a) Estimation of evolution of negative skin friction with degree of consolidation (Alonso et al. 1984); (b) chart for geosynthetic design based of allowable differential settlement (Lawson 2000); (c) influence of height and friction angle of embankment on Efficacy factor (Jenck 2005).

deformation in the head of rigid inclusions may suppose the failure state, as settlements may reach levels corresponding tolarge percent of column diameter. Furthermore, the punching failure in the head and toe of columns occurs immediately after the application of embankment load, and associated risk increases with smaller diameters of rigid inclusion, being quite sensitive to the variation of the soil parameters also.

On the other side, flexible elements like stone columns tend to reduce the punching effects at the base of embankment. In this case the system gives a ductile behavior, whereas, due to column compressibility and its drainage characteristics, the ultimate limit state is reached after large deformation and at the end of consolidation. Therefore, the behavior of such system takes place in the domain of serviceability limit state (SLS).

Wehr et al. (2012) proposed three categories of increasing risks, in order to assess the reliability of ground improvement methods according to their ductility and sensitivity to the variation of soil and materials parameters, taking as a reference the standards DIN 1054 and Eurocode 7. Thus, regarding to columns-type elements, flexible columns with small risks (stone columns, vibro compaction, sand columns) are in category A; rigid columns with diameter larger than 30 cm, which presents an average risk, are in category B; and rigid inclusions with diameters less than 30 cm and non-ductile behavior, which represent a high risk, are in category C.

3.2 Consolidation process

The addition of cement agents disables the drainage capacity of rigid columns, whereby settlements stabilization is obtained only due to a high load concentration on the columns. However, during the consolidation of pore pressures produced by the remaining part of embankment load that act on the soil, an important negative skin friction is generated in the part of columns above the neutral plane, very similar to piles, but without any capacity and structural connections. Consequently, the risk should be assessed due to possible reduction or loss of the load concentration on columns (or efficiency factor) along the lifetime of the CSEs. This situation could occur if certain loss of arching effect happens, as a consequence of possible LTPs deteriorations, e.g. due to internal failure of geosynthetic-reinforcement. In this case, the consolidation would occur in the long term, according to the permeability of the natural soil.

Moreover, it would involve the evolution of neutral plane over the time, dominated by the increase of negative friction. Figure 4a shows an example of this complex mechanism reported by Alonso et al. (1984).

In the case of stone columns, the rapid settlements stabilization is expected due to their drainage capability. Castro and Sagaseta (2009) analyzed the evolution of stress concentration on the stone columns, showing that in the very beginning entire load is carried by the soil, and the final load concentration on the columns is obtained after consolidation (Figure 5). However, after short period of consolidation, effective stress of soil tends to increase, and additionally provides greater confinement to the columns. Such results suppose an improvement of the whole column-soil system.

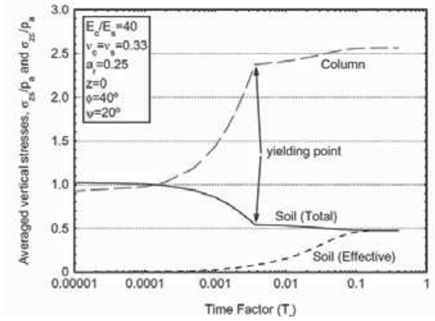


Figure 5. Time development of soil and column stresses, (Castro and Sagaseta 2009)

4 GENERAL ASPECTS OF SAFETY VERIFICATION

There is a range of recommendations that attempt to unify design of LTPs composed by geosynthetic-reinforcement layers, basically used in piled embankments (BS8006 2010, EBGEO 2010, Nordic Handbook 2005). However, the design of column-type elements is redirected to typical pile standards. As it was mentioned in section 2.2, it has to be emphasized, that these recommendations deal with systems where almost entire load is transferred to bearing elements heads, hence negative skin friction is practically negligible. According to what has been stated here about the higher level of risk exhibited by the rigid inclusions with small diameter, the most important safety aspects of such elements will be commented.

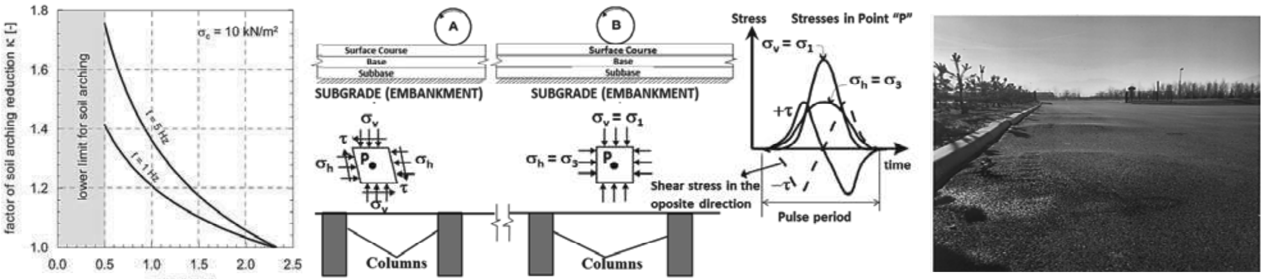
4.1 Large-height embankment

The ASIRI recommendations define two different situations:

Domain 1: if the ULSs are not guaranteed without improvement, rigid inclusions are used to ensure the global stability, and bearing capacity of rigid inclusions for both ULSs and SLSs have to be checked, similarly to the French Eurocode 7 application for piles.

Domain 2: if the ULSs are analyzed for the situation without improvement, then rigid inclusions are used as settlement reducers, and only SLSs have to be proceeded.

Taking into account the ASIRI recommendations, it could be distinguished that when the CSE system comprises embankments with more than 3 to 5 m height, the design is usually focused to guarantee the ULSs. Regarding to the external bearing capacity (GEO) for rigid inclusions, the most important checks against the permanent loads will be punching at their heads and tips, as well as the horizontal stresses, bending moments and shear stresses due to slope failures.Buckling effects have to be checked when soft soil has pressuremeter modulus smaller than 3 MPa.



(a) **(b)** **(c)**

Figure 6. (a) Factor of soil arching reduction (Heitz et al. 2008); (b) stress conditions in the subgrade due to moving load on the pavement surface; (c) pavement deformation due to hard-point effects associated with the presence of rigid inclusions.

Regarding to the structural bearing capacity (STR), a minimum compressive strength of 7 MPa has to be adopted, and no shear stress is allowed for unreinforced columns smaller than 30 cm. Besides, if tension can develop, for Domain 1 the rigid inclusions have to be reinforced, whereas for Domain 2 only an adequate tensile strength of concrete could be adopted.

On the other hand, Katzenbach et al. (2012) have compared the safety checks outlined in the ASIRI recommendations with other guidelines for similar foundation systems usually used in Germany (CSV, CRPF), according to the partial safety factor approach. They reported that ASIRI has lower values of safety factors than those the compared guidelines indicate.

4.2 *Low-height embankment*

In the case of embankments with heights less than 3 meters, the design is usually aimed to guarantee the SLSs, according to the Domain 2. Basically, the geometry of the CSE systems has to be set to avoid excessive deformation in the surface of the embankments, in order to allow an adequate traffic operation. For this objective Lawson (2000) proposed the chart depicted in Figure 4b, for the design of the height and geosynthetic-reinforcement of LTP layers considering the columns as hard points, and according to typical thresholds adopted in transport projects related to differential settlements.

The differential settlements also depend on the LTP strength. Figure 4c shows the analysis of Jenck (2005) related to the influence of the height of the embankment and the strength of unreinforced LTPs in terms of friction angle. Results indicate that efficiency factor E increase with height of embankments until a maximum value similar to the critical height H_C. Also, it can be seen that when LTP is composed by materials with friction angle less than 20 degree the efficiency factor is drastically reduced, and practically negligible when $\phi = 0$.

So far it is not fully analyzed the behavior of CSE against the cyclic loading of traffic. Heitz et al. (2008) have demonstrated that the arching mechanism to transfer load of LTP can only be formed in a very limited extent if geosynthetic reinforcement is not placed. Based on laboratory model tests under cyclic loading, they proposed a soil arching reduction factor, k.

Figure 6a shows this factor depending on the ratio of fill height and column spacing h/s, the frequency *f* and amplitude of the cyclic load σ_c.For rigid inclusion application negative influence of the traffic loading has to be considered during construction and operation stages. Figure 6b illustrates that cyclic loading of traffic can generate the rotation of principal stresses in the subgrade layers, which could cause severe damages to the rigid inclusions and pavement serviceability in the long term, especially for low-height embankments.

Finally, Figure 6c shows an example of pavement deformation due to a combination of the effects mentioned.

5 CONCLUSIONS

The influence of columns stiffness commonly used on the Column Supported Embankment (CSE) systems has to be rigorously investigated in order to establish the implications on the safety and serviceability issues. The facts that indicate the higher risks of rigid inclusions compared with flexible ground improvement methods like stone columns are exposed, especially when diameters of rigid inclusions are smaller than 30 cm. Moreover, the requirements of LTPs in terms of strength and thickness, has to be more strict for rigid inclusion comparing with stone columns, in order to ensure the arching load transfer in the long term behavior of the CSEs, for both static and cyclic loading.

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