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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.

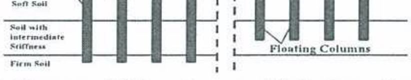
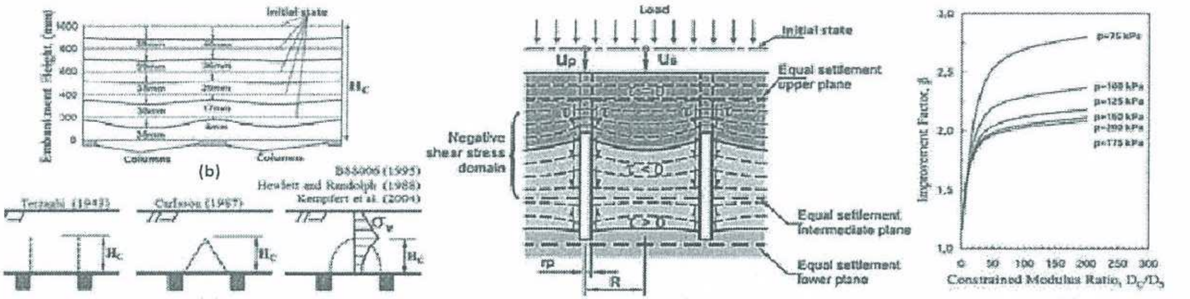


Figure 1. Elements of Column Supported Embankment Systems



(a) (b) (c) (d)

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).

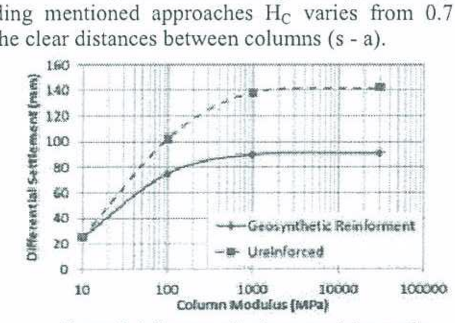


Figure 3. Influence of column modulus on the differential settlements within Load Transfer Platform (Gangakhedar 2004).

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). 1°

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