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SEISMIC PERFORMANCE OF MIXED MODULE COLUMNS ; PHYSICAL AND NUMERICAL MODELLING OF INERTIAL INTERACTION

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ABSTRACT

Vertical rigid inclusions are widespread as a solution for ground reinforcement of soft soil. They can considerably increase the bearing capacity of foundations and reduce the settlement. However, under seismic loading, damage might arise in rigid inclusions which are made of plain concrete. The ground reinforcement by Mixed Module Columns (CMM®) combines the advantages of increase in bearing capacity and reduction in settlement due to the lower rigid inclusions with a dissipation of the energy in the flexible stone columns in its upper part. In this paper, a first approach of the seismic performance of (CMM®) and rigid inclusions is presented through both physical and numerical modelling. A series of tests in a large tank filled with saturated clay is presented. Two reduced models with a scale of 1/10 of a square shallow foundation lying on the soft clay reinforced by either Mixed Module Columns CMM® or Rigid Inclusions associated to a granular layer (IR) were tested under quasi-static and dynamical horizontal cyclic loadings. In parallel, a numerical modelling of the CMM® was carried out with the computer program FLAC^{3D}. The comparison of the experimental and numerical results put into evidence the inertial effects occuring in the dynamic tests and the dissipation of most of the seismic energy in the upper part of the Mixed Module Columns, with its high flexibility due the presence of the soft clay between the soft columns.

Keywords: Mixed Module Columns, rigid inclusions, seismic soil-inclusion interaction

INTRODUCTION

Mixed Module Columns (CMM®) is an alternative solution for the widely used soil reinforcement techniques, such as stone columns and rigid inclusions. It combines the features of these two techniques and seems to present an interest for foudation projects in seismic areas. A CMM® is composed of two parts : an upper part in compacted gravel (short stone column) overlaying a rigid inclusion in its lower part. A transition zone links the two parts (Bustamante et al., 2006).

When using rigid inclusions as reinforcement of soft soil, the inclusions need often to be reinforced by steel elements or to be associated with a granular mattress in order to sustain horizontal loadings related to wind or earthquakes. These shortcomings can be avoided through the execution of the upper part of the

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CMM® in expanded gravel. This upper part, more flexible in its interaction with the surrounding soft soil, acts as a dissipative rotulated zone which transmits less energy towards the superstructure by direct effect and less energy downwards to the rigid part of the CMM® by inertial effect.

Many studies have been carried out on vertically loaded shallow foundations lying on soft soil reinforced by stone columns, or vertical rigid inclusions, or vertically and laterally loaded pile foundations (Chenaf 2006, Georgiadis et al. 1992, Li & Byrne 1992, Rosquoët et al. 2007, Thorel et al. 2010, among others). However, less work has been found on reinforcement by CMM® in seismic areas (Hatem et al. 2009).

This paper presents the study of the response of a square footing with 2 m width embedded in very soft clay reinforced by four CMM® and submitted to cyclic horizontal loading. Physical models in 2D were tested at a scale 1/10 in the large tank "VisuCuve" of Laboratoire 3S-R in order to visualise and analyse the interaction mechanisms. Quasi-static and dynamic loadings were applied to the foundation model in order to evaluate the inertial effects. The response of a CMM® system was compared to the one of a similar system combining rigid inclusions and a complete gravel mattress. The real case of a footing supported by four CMM® was simulated numerically, with the height of the upper part in compacted gravel which was varied in order to determine its influence on the response of the rigid lower part.

PHYSICAL MODELLING

Presentation of the physical models

The reduced model presented in this work is submitted to a normal gravity "g*=1" and the conditions for a rigourous similitude with respect to the stress level "σ*=1" are not fulfilled. Even though the scaling laws are not strictly respected, the main objective of the physical modelling was to visualize the interaction mechanism of the complex soil-CMM®-footing under horizontal loading and to calibrate a numerical model.

Two reduced models with a scale of 1/10 of a square footing with a width of 20cm and a thickness of 2cm were realized. They were installed on soft clay reinforced either by the CMM or the IR. The dimensions of the system and the mechanical parameters of the soil are summarized on Figure 1.The clay mass was produced by the mixture of two types of clay and adapting the water content of the mixture in order to obtain a given value of the undrained shear resistance (Orozco et al. 2007). The CMM were modelled in 2D by two rectangular sections (20cm*9cm) filled with gravel for the upper part (simulating the stone columns) and two aluminium plates with a rectangular section (20cm*0.3cm) for the lower part (simulating the rigid inclusions). The lengths of the upper and the lower part were respectively 10cm and 50cm, and the lower part was embedded into underlying granular layer at a depth of about 5cm. The axial distance between the two CMM® models was 12cm. The heads of the rigid part of the CMM® were embedded into two horizontal PVC plates simulating the transition zones and supporting the gravel, in order to create conditions close to the real connection between the two parts. Two geotextile socks were used to avoid the penetration of the upper part gravel into the surrounding soil. Also, an abrasive paper was stuck to the surfaces of the footing model and the PVC plates to get a better transmission of the horizontal force applied to the footing model to the heads of the rigid inclusions. The foundation model was embedded into the soil of its whole thickness. In the IR model with soil mattress, the same configuration was reproduced, with a continuous granular mattress being substituted to the upper part of the CMM®.

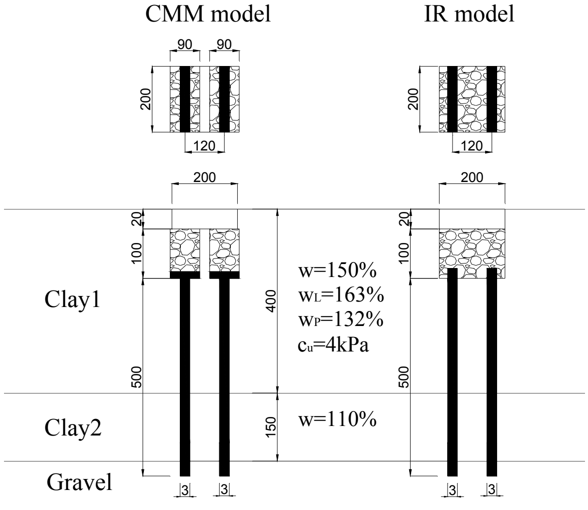

Figure 1. Configuration and the dimensions of the 2D physical models (mm)

Experimental methodology
The experiment setup "VisuCuve", shown in Figure 2, consists of a large rigid and impervious tank of 2m long, 1m wide and 1m deep, allowing a lateral visualization of the mechanisms. It is filled with very soft saturated clay underlain by a granular rigid stratum. The physical model was placed on the side near the window to visualize the deformation mechanisms during the experiment. A second identical model was built on the other side in order to allow the system to work symmetrically. A trolley supporting the foundation model was installed above the tank and could slide along two rails fixed on the two long sides. With a vertical guidance system on the trolley, the foundation model can freely settle down under the loading. Two horizontal loading systems were used respectively for quasi-static experiments and dynamical experiments. For the quasi-static experiments, the trolley was connected to a ball-screw system with a brushless motor.

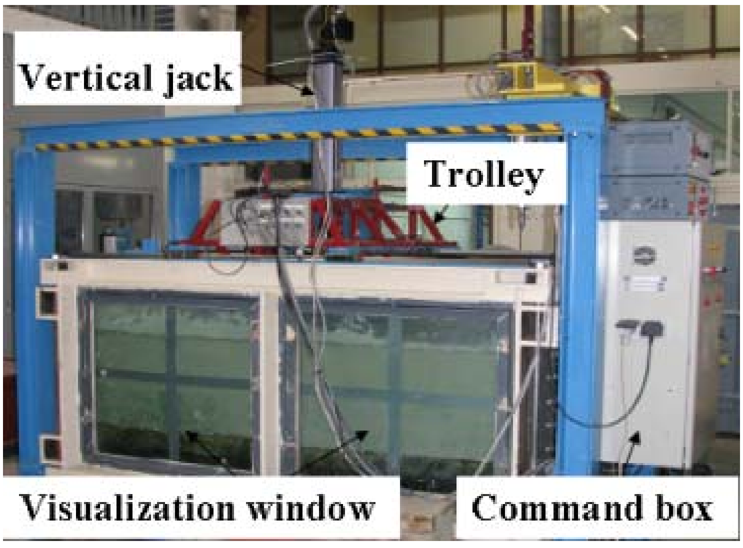

Figure 2. Photo of the visualisation tank

For the dynamic ones, a fast electro-mechanical actuator with a maximum velocity of 700mm per second was used. It is a roller screw type linear actuator EXLAR FT35-2410-FIA-EX4-L2 mounted with a high performance brushless motor, allowing a variable-frequency drive. The vertical loading was kept constant during the tests and applied by putting weights directly on the foundation model. The horizontal and vertical forces were measured by two load cells fixed on the loading system. The horizontal displacement of the foundation model was controlled by a large displacement sensor mounted on the trolley in the quasi-static tests and a LVDT on the foundation in the dynamical tests. The vertical displacement was measured by a vertical LVDT fixed on the foundation model.

After completing the filling of the tank with clay and an ageing period to ensure homogeneity of the soil mass, the thin aluminium plates modelling the rigid part were inserted vertically into the soil by hand. The insertion of the plates into the soil was performed carefully to keep them well vertical all along the operation. At the end of the installation, when the plates came into contact with the gravel at the bottom of the tank, they were hammered into the gravel to reach an embedment depth of 5cm. For the CMM® model, 6cm wide trenches were excavated till the head of the rigid inclusion. The PVC plates attached to the "geotextile sock" were then placed horizontally on the rigid inclusion at the bottom of the trench. Subsequently, gravels (2mm-4mm) were put into the trench progressively and compacted to the predefined width. For the IR model, the granular layer was formed by putting directly the gravel above the aluminium plates, embedding the heads of the plates over 1cm into the gravel. Then, the trolley supporting the foundation model was moved above the stone columns or the granular layer. Finally, a layer of clay of 2cm thick was deposited around the foundation model to form the embedment before applying the loading.

Once the foundation model was in contact with the reinforced soil, the vertical force was applied by a total weight of about 500N. Forty cycles of horizontal cyclic loading were then applied with a constant displacement amplitude of 5mm. The frequency was 0.05Hz in the quasi-static tests and 1.2Hz in the dynamic tests (Zhang et al., 2010a).

Results analysis

During the quasi-static tests, the upper gravel parts of the CMM® move horizontally together, but with an amplitude of the horizontal displacement gradually decreasing with depth. At the same time, these gravel parts were expanding laterally, especially in their upper part, inducing a significant settlement of the foundation. Also, the surrounding soil was removed laterally away from the upper gravel parts. This can be explained by the combined effects of the vertical and lateral loadings applied to the foundation model which were transmitted to the upper gravel parts. Lateral movements were only observed in the upper parts of the CMM®. The PVC plates and the heads of the aluminium plates were not found to move. Apparently, the transmission of the horizontal load is strongly reduced over the height of the upper gravel part and the lower rigid part of the CMM® seems to undergo only vertical loads during the horizontal cyclic loading. A similar behaviour was observed in the model combining rigid inclusions and a thick gravel mattress.

During the dynamic tests, the amplitude of the movement of the two models is higher, either in the upper part of the CMM® or in the granular mattress above the rigid inclusions. Also, a horizontal displacement of the heads of the rigid inclusions (aluminium plates) could clearly be observed in both models. It turns out that a more important part of the horizontal load is transmitted to the rigid inclusions due to the inertial effects. But no displacement of the rigid inclusions was observed in the vertical direction, like in the static tests. Two photos of the CMM model are shown in the Figure 3 before and after the experiment.

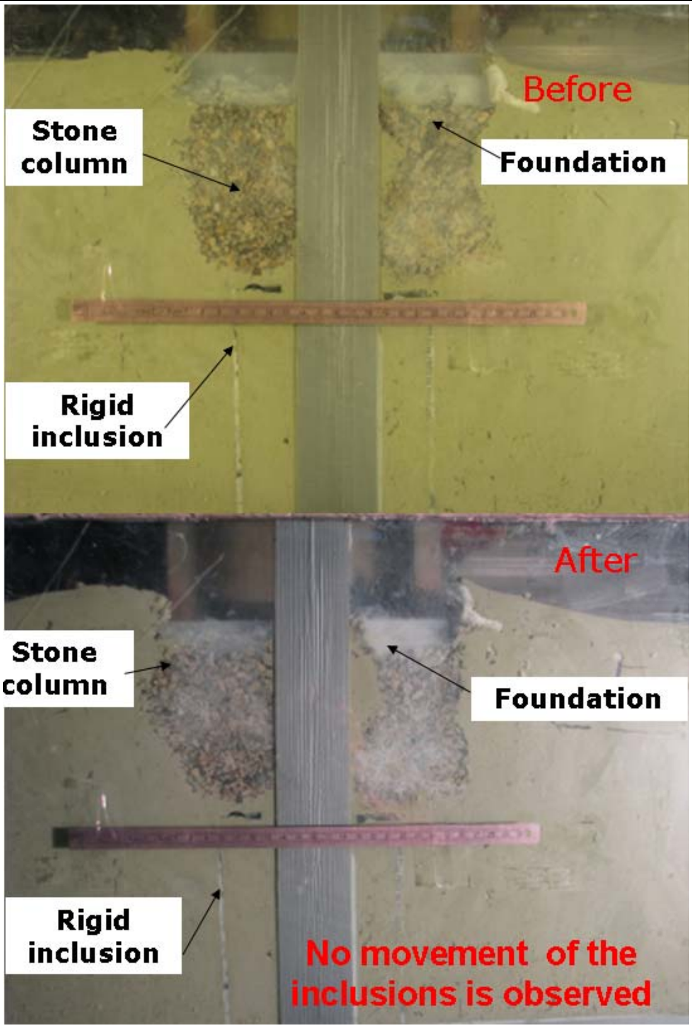

Figure 3 . Views of the CMM® model , Quasi static sollicitation

The settlements of the foundation measured during the experiments are presented in Figure 4. The strong values of the settlements can be related to a plastification of the system occurring rapidly in this soft clay with a very weak undrained shear resistance of 5 kPa. The accumulation of the settlement was more significant for the first cycles, while it tends to stabilize later. For both models CMM® and IR, the settlements in the quasi-static test are lower than those in the dynamic test. This difference is particularly strong for the IR model, but this fact may be due to a progressive local punching of the mattress above the head of the inclusion due to a weak compaction.

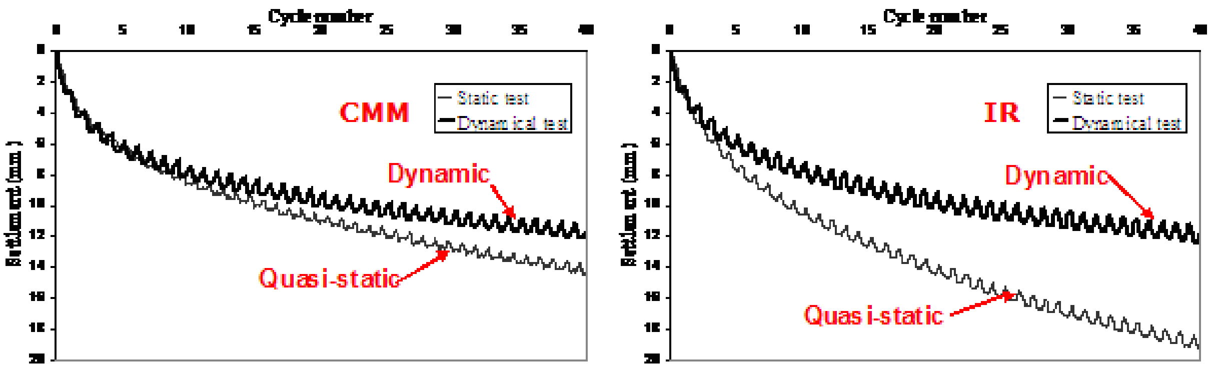

Figure 4. Settlements of the CMM® and IR models during the test

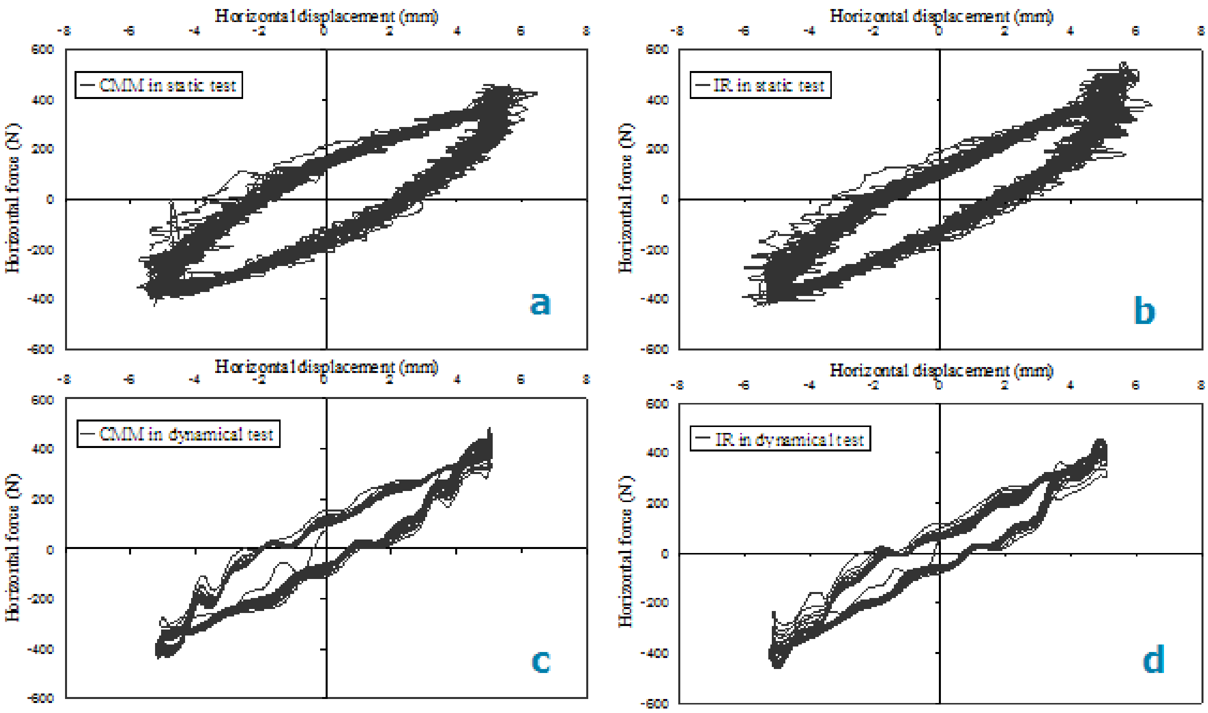

Figure 5. The horizontal force-displacement response of the foundation for CMM® and IR models in static and dynamic solicitations'

The horizontal force-displacement plots of the two models presented in Figure 5 show that the horizontal stiffness remains constant with the number of the cycles for both quasi-static and dynamic tests. The hysteresis loops illustrate the energy dissipation during the cyclic loading, in the upper part by the friction at the soil-foundation interface and inside the soil mass by the interaction between the gravel and the surrounding soil. It can be seen that the hysteresis loops in the dynamic tests are smaller than those in the static ones. That means less energy dissipation happened during the dynamic tests. This corresponds to what was observed during the experiments and indicates that a more important part of the horizontal load was transmitted to the heads of the rigid inclusions in the dynamic tests. It can be noted from Figure 5 that the hysteresis loops for the CMM model are slightly larger than those of the IR model in both quasi-static and dynamic tests, which means that the CMM system can dissipate more energy than the IR system.

NUMERICAL MODELLING OF THE CMM®

Presentation of the numerical model

The computer program used is FLAC^{3D} (Fast Lagrangian Analysis of Continua in 3 Dimensions). It is a three-dimensional explicit finite difference program for engineering mechanics computation designed by Itasca Consulting Group Inc. It simulates the behavior of three dimensional structures built of soil, rock or other materials that undergo plastic flow when their yield limits are reached. The dynamic analysis option permits to resolve the full equations of motion, using the fully nonlinear method embodied in FLAC^{3D}, rather than the "equivalent-linear" method which is commonly used in earthquake engineering for modeling wave transmission in layered sites and dynamic soil-structure interaction. The fully nonlinear method follows any prescribed nonlinear constitutive relation, and irreversible displacements and other permanent changes are modeled automatically.

The studied foundation system consists of a square footing 2m wide and 0.5m thick. It is totally embedded in the soil. Four (2*2) CMM® are placed in the soil under the footing. The upper part of the CMM® is a stone column with 0.9m diameter and varying length (0.3m, 1.0m and 1.5m). The length of the upper part of the CMM® was varied in order to examine its influence on the behaviour of the rigid inclusion in the lower part (Figure 6). The lower part of the CMM® is a rigid inclusion made of plain concrete with 0.34m diameter, with a length of 5m. Between the upper and the lower part is an area called "transition zone" which has the same diameter as the stone column and a length of 0.5m. The transition zone is designed to better transmit vertical loading to the lower part and consists of a mixture of concrete and gravel. The axial distance between the CMM® is 1.2m, so it is observed that the area of the CMM® exceeds slightly the square footing. Two soil layers were taken into account in the numerical modeling. A soft clay layer and a more resistant gravel layer to obtain the embedment of the rigid inclusions. The dimensions of the different parts of the foundation system are illustrated in Figure 6.

Within the numerical models, system composed of footing, stone columns with the "transition zones" and soil media was discretized using predefined 6-node radial cylinder elements and 8-node brick elements (Figure 7). In fact, finer meshes could lead to more accurate results because they provide a better representation of high-stress gradients. Numerical studies on piles by FLAC^{3D} have shown that the finer meshes hardly improve the results. The mesh employed here is rather coarse to find a compromise between the accuracy and the calculation efficiency. The rigid inclusions were modeled by three-dimensional pile elements and each rigid inclusion was discretized in ten pile elements. In addition, to provide the structural behavior of a beam in FLAC^{3D}, both a normal-directed and a shear-directed frictional interaction occur between the pile and the grid. Each pile structural element is defined by its geometry, material and coupling-spring properties. A pile element is assumed to be a straight segment of uniform, bisymmetrical cross-sectional properties lying between two nodes. For the heads of the rigid inclusions, the nodes of the pile element were linked rigidly to the "transition zones" in the three displacement directions (no relative displacement between the grid and the node) and free in the three rotational directions. To form the embedment of rigid inclusions in gravel layer, the links between the pile element nodes and the gravel layer were set rigid in all the degrees of freedom.

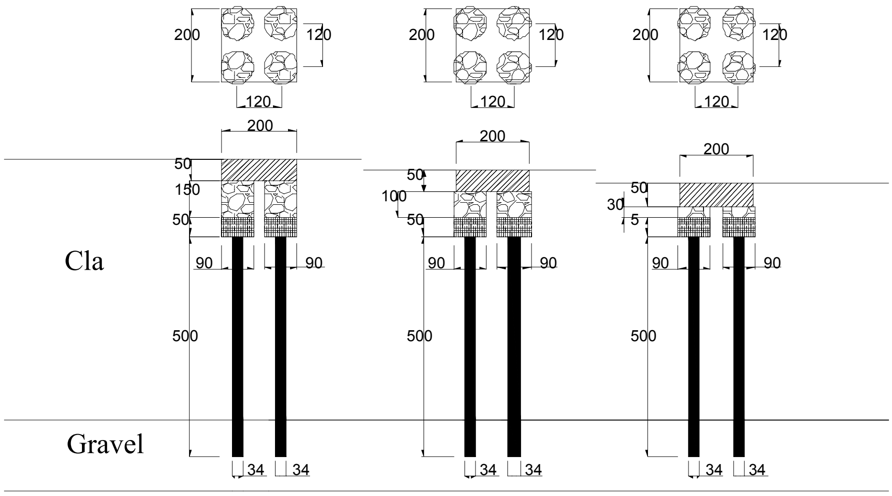

Figure 6. view and dimensions of the numerical model (cm)

The behavior of stone columns, soft clay and gravel layer was described by an elastoplastic constitutive model based on the non-associated Mohr-Coulomb criterion. The Mohr-Coulomb model is the simplest elastoplastic constitutive law which presents quite satisfactory results with not many soil parameters required. Linear elastic model was applied to the footing, “transition zones” and rigid inclusions. The contact conditions between the foundation and the soil were simulated by interface elements of Mohr Coulomb type. The properties of the interface elements were determined according to the type of soil which they were in contact with. The same type of interface between the piles and the soil were used via the pile elements. The cohesion and the friction angle of the concrete-clay interface were respectively 0 kPa and 38°, while the values were changed to 20 kPa and 0° for the concrete-gravel interface. All the material parameters are summarized in Table1. It can be noted that a higher value was adopted for the Young’ Modulus of the rigid inclusions under dynamic loading than under the static loading ($E_{dyn} = 3*E_{stat}$), which is commonly used in geotechnical engineering.

Table 1. Material parameters for the numerical model

	CB	Clay	Gravel	Transition Zone	Rigid Inclusion	Foundation
Young Modulus (Mpa)	60	6	100	600	5285	1000
Poisson Coefficient	0,3	0,3	0,3	0,3	0,2	0,2
Friction Angle (°)	38	0	45			
Cohesion (kPa)	0	20	0			

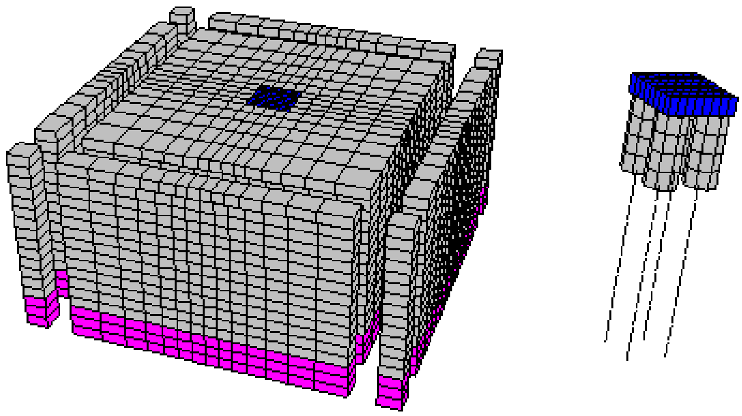

Figure 7. The grid of the numerical model of the CMM® system

Results and analysis
The numerical modeling was carried out in three calculation stages. First of all, in the first stage, a vertical loading was applied to the footing until the soil collapsed, in order to obtain the bearing capacity of the foundation. Then, in a second stage, a horizontal loading was applied to the foundation coupled to a nominal vertical loading. The maximum horizontal loading was determined when the footing tended to slide. Finally, in the third stage, a dynamic horizontal cyclic loading was applied with the same vertical loading as in the second stage.

In the first calculation stage, in order to investigate the ultimate vertical bearing capacity, a static vertical loading was applied to the footing by means of a very slow continuous displacement. The conventional ultimate vertical load is defined when the settlement of the foundation reaches 10% of the foundation width, which is 20cm here. Figure 8 shows the distribution of the axial forces in the rigid inclusions when the footing was loaded vertically with a nominal vertical load determined by applying a safety factor of 3 to the bearing capacity of the 1.5m long CMM system, i.e. Q=320kN. The length 0 corresponds to the heads of the rigid inclusions. Because of the symmetry, only one rigid inclusion for each case is studied here. The CMM system with 0.3m long stone columns has a much higher bearing capacity than the two others. The length of 0.3m for the stone columns is so small that their behavior is quite similar to a pile foundation. While for the two others, the stone columns are longer and almost all the settlement takes place inside the stone columns and the surrounding soft clay layer. Due to the different settlements between the stone columns and the soft clay, negative friction occurs on the upper part of the rigid inclusions. This explains the increase of the axial forces in the rigid inclusions till a neutral point, followed by the classical decrease towards the base. It was also verified that the axial forces in the rigid inclusions decreased when increasing the length of the stone columns.

In the second calculation stage, with nominal vertical force defined previously (Q=320 kN), the footing was subjected to a horizontal loading by means of a very slow continuous displacement. The maximum horizontal displacement before sliding was around 12mm. The nominal horizontal loading was defined when the displacement attained 4mm (safety factor of 3) which corresponded to a horizontal force of about H = 130kN.

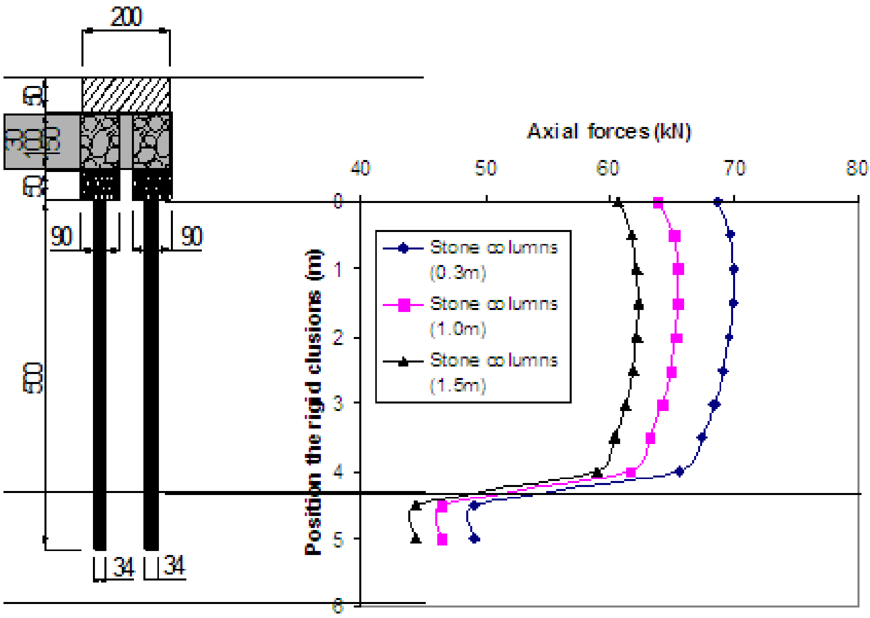

Figure 8. Axial forces in the rigid inclusions (Q=320 kN) for CMM system

Figures 9a, 9b, 9c present internal forces in the rigid inclusions under the nominal vertical Q and horizontal H loadings. The maximum shear forces were obtained at the heads of the rigid inclusions, while the bending moments attained the maximum values about 1m below. It can be seen that all the internal forces have a decreasing tendency when the length of the upper part stone columns in the CMM® system increases. It is also observed that the internal forces in the front rigid inclusion are larger than those in the behind one, which agrees well with the pile-group effect. Note that there is a phase difference of the responses between the front and the behind rigid inclusions. Values are the same in the down part due to nodes are fixed in the modeling.

In the third calculation stage, with the nominal vertical charge Q applied, the dynamic analyses were performed under a horizontal cyclic loading with a sinusoidal form. The amplitude of the loading is 4mm, which was determined beforehand by the static horizontal response in order to compare their results. The dynamic loading has a frequency of 1Hz and lasted 10 seconds. The horizontal displacement was applied to the footing by means of the velocity imposed through all the dynamic time steps.

During the dynamic loading, after a transition stage, no changes were observed in the response of rigid inclusions from the 3rd cycle to the 10th cycle because the soil-footing-CMM stabilization has been obtained. The envelopes of the internal forces in the rigid inclusions during the dynamic loading are illustrated in Figure 9d, 9e, 9f. Because of the symmetry of the dynamic loading, only one of the rigid inclusions is studied here. Due to the inertial effect, the response of the rigid inclusions in the dynamic analyses is more evident than in the static calculation. This agrees well with the observation during the 2D dynamical experiments in the visualization tank (Figure 2). The movement of the heads of the rigid inclusions was quite evident, while it didn't exist at all in the static ones. That means the rigid inclusions were much more loaded in the dynamic tests, which corresponds to the numerical results. The maximum bending moment here is almost twice larger than the static case. The shearing force at the top is also larger in dynamic compared to static.

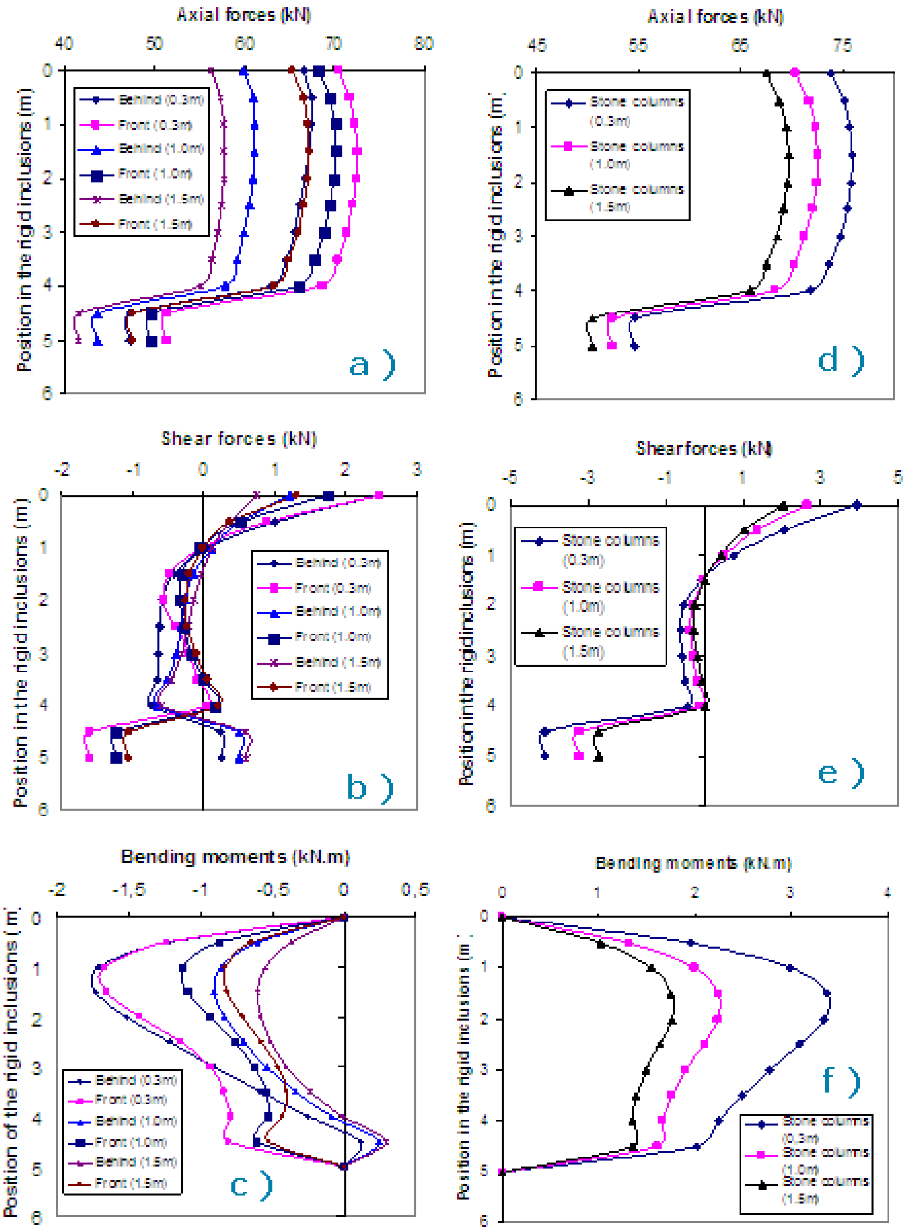

Figure 9. The response of the internal forces in the rigid inclusions; front and behind under the static horizontal loading, 9a) Axial forces, 9b) Shear forces, 9c) Bending moments; the envelopes under the dynamic loading, 9d) Axial forces, 9e) Shear forces, 9f) Bending moments.

Finally, the same tendency with respect to the effect of the length of the stone columns is observed: longer are the stone columns, lower is the strength response in the rigid inclusions. The shear force is strongly reduced, from 130 kN applied to the footing to only 4.1 kN at the head of the rigid part of the four CMM® having a length of 1.5m of stone column. The rigid part of the CMM® keeps in compression over all its length for values of the height of the flexible part of 1.0 m and 1.5 m.

CONCLUSIONS

A study of the response of ground reinforcement by Mixed Module Columns CMM® under dynamic horizontal loading has been performed through physical and numerical modelling.

The results of 2D experiments indicate that the system CMM® dissipates an important energy in its flexible upper part, much more than in the granular mattress of a system with mattress and rigid inclusions. Horizontal displacements of the heads of the rigid inclusions were observed in dynamic loading, and not in quasi-static loading.

The results of the 3D numerical modeling put into evidence that the length of the upper flexible stone columns has an important influence on the response of the lower rigid inclusions. The longer the stone column is, the less the rigid inclusion is loaded. The decrease in the shear forces through the upper part is very high and can reach 97% for a height of 1.5m. The comparison of the results between the static analysis and the dynamic one showed that there was an important inertial effect on the internal forces of the rigid inclusions.

In a further research program, physical models in three dimensions will be built to calibrate the numerical models and to confirm these first tendencies.

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