Experimental study to correlate change in the structural frequency and foundation soil water content

Etude expérimentale qui permet de corréler le changement de fréquence structurale et le contenue d'eau dans le sol de bassement.

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ABSTRACT

The existence of an important infrastructure stock with extended usage periods that has suffered damage or collapse under conditions of normal functioning or external actions that are slightly higher than normal has raised the interest of the scientific community for the development of a structural health monitoring technique. It has been identified that the variation of these dynamic parameters depends mainly on the mass and stiffness of the structure. However, it has been observed recently that temperature, rain and wind also affect the dynamic parameters of the system. In practice, it is difficult to determine if the observed changes in these parameters are caused only due to structural effects, or also due to climatic changes. This article presents results of a study conducted to investigate the effect of soil water content in the natural frequency of a scale soil–structure system.

RÉSUMÉ

Il, existe une quantité importante d'infrastructures dont l'utilisation a été faite pendant de longues périodes, et qui ont souvit des dommages, on qui ont collapse sous des contraintes normales, ou des perturbations extérieures, un peu au dessus du normal. Ceci a intéresse la communauté scientifique pour développer des techniques de surveillance de l'état de surette des structures. On a identifie que la variation des propriétés dynamiques dépend de la masse et de la rigidité de la structure. Cependant on a observe recentrement que la température, la pluvier, et le vent intervient aussi sur les paramètres dynamiques du système. Dans le pratique, il est difficile déterminer se les changements observes de ces paramètres sont ils dues seulement aux effets structurales, ou dues aux changements climatiques. Ce travail présent des résultats d'une étude qui s'adresse a cherché l'effet du contenu d'eau dans le sol sur la fréquence naturale d'un système sol-structure en utilisant un modèle mis en échelle.

Keywords : structural health monitoring, natural frequency, water content, scale model.

1 INTRODUCTION

The process of implementing a damage detection strategy for civil engineering infrastructure is referred as structural health monitoring. This technique is based in that the changes in the physical properties of a structure, such as mass, stiffens, and damping modifies its dynamic parameters. Therefore, if changes in dynamic properties like natural frequency and vibration modes are registered, it is possible to detect changes in physical properties and damages in the structure. The implementation of structural health monitoring is growing every day, since it requires a basic instrumentation and uses a non destructive method based on the measurement of ambient and seismic vibrations. However, in the last few years investigations of monitored structures have detected that some of their dynamic parameters not only changed due to physical changes of the structure but also due to climatic variations.

The first case registered corresponds to the Millikan Library of the Californian Institute of Technology, located in Pasadena (Clinton et al., 2006). In this reinforced concrete 9 story building the researchers observed a correlation between changes in the natural frequency of the structure and strong rains that occurred during 2003. Figure 1 shows the time histories of changes of the mean natural frequency in the three directions, as long as temperature, wind velocity and amount of rain. The amount of fallen water in that zone was of 100 mm in a period of two days, increasing the natural frequency of the structure in 3% in the east-west and torsional direction. It is possible to observe that after a couple of days the natural frequency tended to go back to the previous values before the precipitation. The figure shows as well a reduction in natural frequency of 3% in the east-west direction due to an increment of the wind. On another hand, variations of natural frequency of the structure in 1% were registered with a considerable increment in ambient temperature.

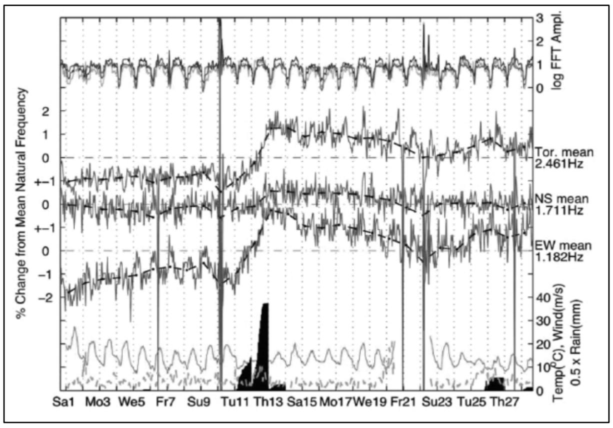

Figure 1. Time histories of changes of the Millikan Library mean natural frequency and atmospheric parameters, (Clinton et al., 2006).

Based on the registers of the Millikan Library it has been developed a mathematical model using the Biot theory for wave propagation within porous medium, in order to obtain equations of elastic waves propagation within a porous sediment (Todorovska and Al Rjoub 2006a). The results of this investigation correspond to two cases (Todorovska and Al Rjoub 2006b), the first one is similar to the Millikan Library and the second one corresponds to the same structure, but located in a more rigid soil. It was observed that stiffness and

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rotational damping of the structure were not affected by the soil water content, while the stiffness and damping in the horizontal and vertical directions were affected by the amount of water in the soil. For the first case, that simulates the conditions of the Millikan Library, the change in natural frequency of the first mode of vibration was in the order of 1-2%, which replicates well the response of the building.

Another registered case corresponds to the Chilean Construction Chamber building, located in Santiago, Chile. In order to keep investigating the climatic effects in the dynamic response of a building, Lazcano (2008) carried on between May and November of 2007 a continuous register of ambient and seismic vibrations of this 20 story concrete building. The main objectives were to identify the model parameters of the building and analyze the dynamic changes as function of climatic variations. This building has been instrumented and monitored since 1995 using the network of 12 accelerometers that belongs to the Civil Engineering Department of the University of Chile. Between June 13th and June 15th rained in Santiago 40 mm and it was possible to observe and register an increment of 1.2% in the natural frequency of the structure-soil system. This variation started to show up as soon as the rain began, increasing during the precipitations and decreasing afterwards once the rain stopped.

In conclusion, it is difficult to determine in practice if the observed changes in the dynamic parameters are caused only due to structural effects, or also due to climatic effects. This article presents preliminary results of an investigation conducted at the Civil Engineering Department of the University of Chile, in order to investigate the effect of soil water content in the natural frequency of a scale soil–structure system. This structure was subjected to excitations in the laboratory and its dynamic response was registered for different soil water contents.

2 SCALE MODEL AND TEST CHARACTERISTICS

The scale model consists in a structure with a foundation embedded in a soil, located inside a cubic wooden box, as shown in Figure 2. The structure is composed of a metal mass, two aluminum columns and a wooden foundation. The top mass, 2728 gr., was determined in order that the natural period of the structure was close to 1 second. The box dimensions are 90cm x 90cm x 90cm and the foundation dimensions are 9cm x 9cm x 30cm. The box was covered inside by a rubber membrane to avoid any loss of water from the model. The soil used corresponds to a silty sand with a water content of 2%, which was placed and compacted inside the box in layers of 5 cm, reaching a density of 1.47 gr/cm3, corresponding to 70% of the Modified Proctor. The instrumentation consisted in one accelerometer, type Kistler 8310A2, located on top of the structure, and three water content sensors, P5, P10, and P20, located at depths of 5cm, 10cm, and 20cm respectively. These sensors were located while the soil was being installed inside the model, and the locations were selected in order to register the soil water content near the wall of the foundation, just below the foundation, and at a depth below the foundation inside the bulb of stresses generated by the structure. Figure 3 shows the sensor P5, when it was being installed near the wall of the foundation. These sensors model MP406 and produced by the ICT International company have a high frequency moisture detector, which use the standing wave principle to indicate the ratio of two or more substances forming a body of material, each substance having a different electric constant. The moisture measurement of the material is based upon the fact that in a water-soil-air matrix, the dielectric constant is dominated by the amount of water present. Then the soil water content can be measured exactly because changes in water content of the soil result in changes in the dielectric constant of the soil. The three sensors were calibrated using a small container of known

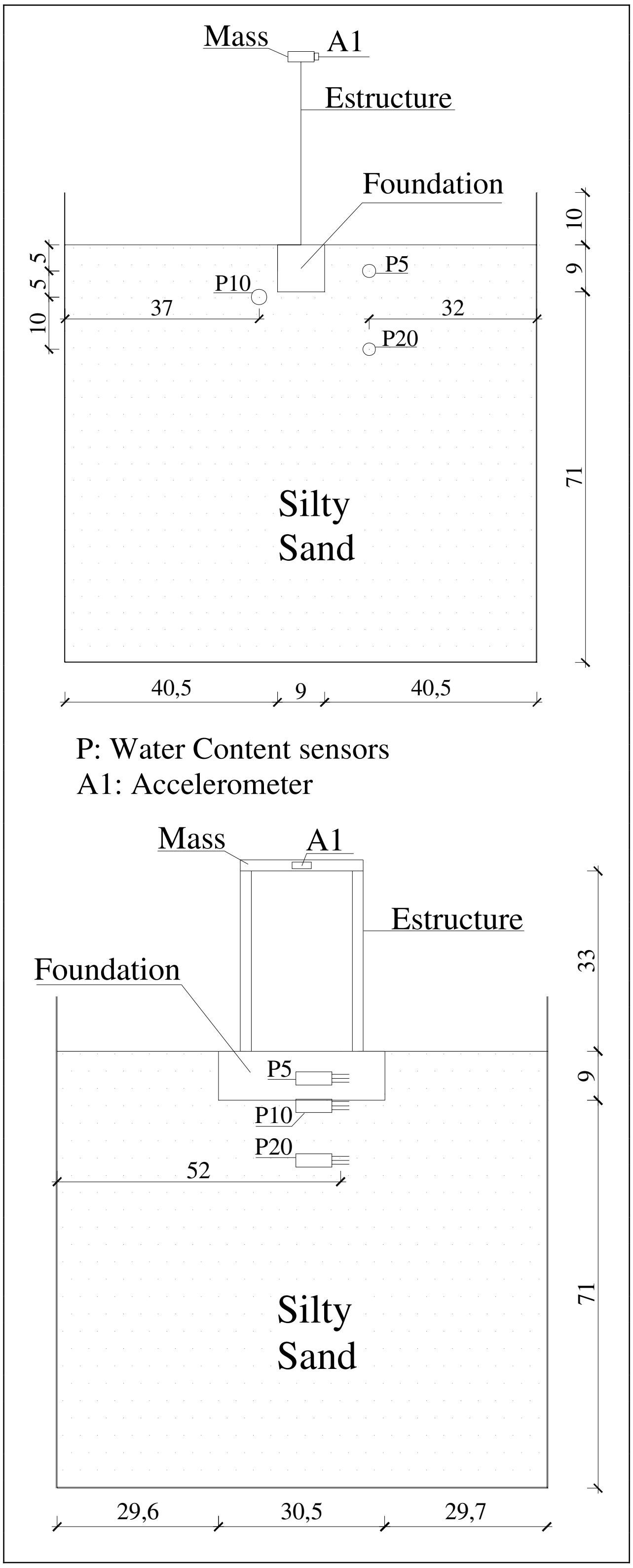

Figure 2. Diagram of the scale model (Units in cm).

volume filled with soil at different water contents. Once the soil inside the box reached a high of 71cm, the structure (mass, columns and foundation) was installed in place. Afterwards, more soil was in put inside the model until the soil surface reached the top of the foundation.

Once the model was finished the mass of the structure was slightly displaced laterally in the more flexible direction and left in free vibration for a reasonable period of time. The natural frequency and damping of the soil-structure system was determined using the acceleration record. This procedure was

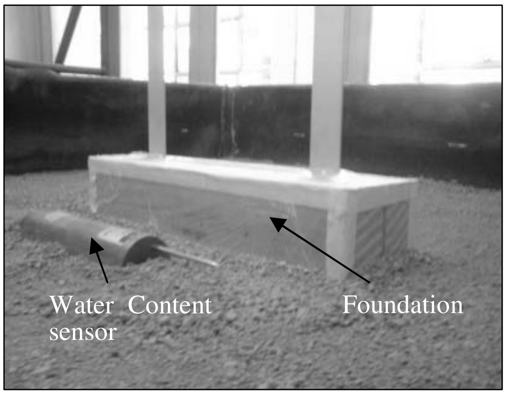

Figure 3. Water content sensor P5, located near the wall of the foundation

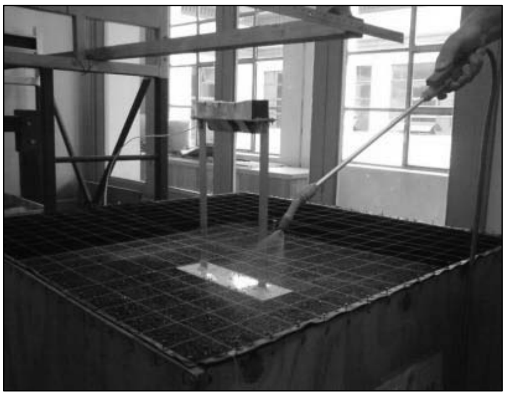

Figure 4. Instant when water is sprayed on top of the model

repeated several times in a period of 10 days, during which water was added in the model using a spray system, as shown in Figure 4, simulating the rain effect. The soil water content using the three sensors was recorded during this period of 10 days. The first test was conducted using a soil water content of 2%; afterwards, water was sprayed on top of the model the first, second, and third day amounts of 5, 10, and 10 liters respectively. The main objective was to analyze the change in the natural frequency of the system, as the profile of soil water content was changing along the depth of the model. Once the 25 liters of water were sprayed on top of the model, the measurements continued for 7 days in order to observe the variation in the natural frequency as long as the soil water content was decreasing.

3 EXPERIMENTAL RESULTS

Figure 5 shows the natural frequency and soil water content registered at 5, 10 and 20 cm depth, for the period of 10 days. The times at which water was sprayed to the model are also specified in the figure, represented as “5 liters” and “10 liters”. The first 5 liters were added at time 0, the following 10 liters at 20 hours and the last 10 liters at 42.5 hours. It is possible to observe that the natural frequency decreased every time water was added to the model. When the first 5 liters were added the natural frequency decreased 0.45%. This value practically did not change after 20 hours, as shown in Figure 5. Once these 5 liters were added the soil water content increased mainly in the first 5 to 7 cm of depth. When the following 10 liters were added, at a time of 20 hours, the sensors P5 and P10 registered a significant increase in water content within a period of one hour, reaching a degree of saturation of 30% for the 10 cm closer to the soil surface. Within this period of one hour (20 – 21 hour) the water content at 20 cm depth practically did not change. After 5 hours of having added water (at 25 hours), the degree of saturation started decreasing in the 10 cm closer to the soil surface and increased below the depth of 10 cm. Similarly than when the first amount of water was added, the natural frequency just after the 20 hours decreased quickly, reaching at the time of 23 hours a variation of 1.25% with respect to the initial value. Unlike in the previous case, after the natural frequency decreased it started increasing reaching a value of 0.939 at 42 hours, the same value that the system had just before adding the first 10 liters of water (at 19 hours). If we compare the soil water content at 19 hours and 42 hours, just before adding the 5 and 10 liters respectively, it is possible to observe that the soil water content is larger in the last case at 10 cm and 20 cm depth, therefore below a depth of 10 cm, and that the water content was similar in both cases closer to the soil surface.

Once the last 10 liters of water were added, at 42.5 hours, the soil water content registered in the three sensors increased immediately, meaning that the water was able to move faster once the voids between soil particles had a minimum amount of water. However, after a couple of hours the water content in the first 20 cm started decreasing, showing that the water was moving deeper within the model. The natural frequency decreased once again when the last 10 liters of water were added, reaching a value similar to the one registered just after water was added for the second time, at 20 hours. In both cases the soil water content within the first 10 cm depth near the soil surface was practically the same, as shown in Figure 6, which is not the case below the 10 cm depth. Afterwards, the natural frequency increased quickly until the time corresponding to 70

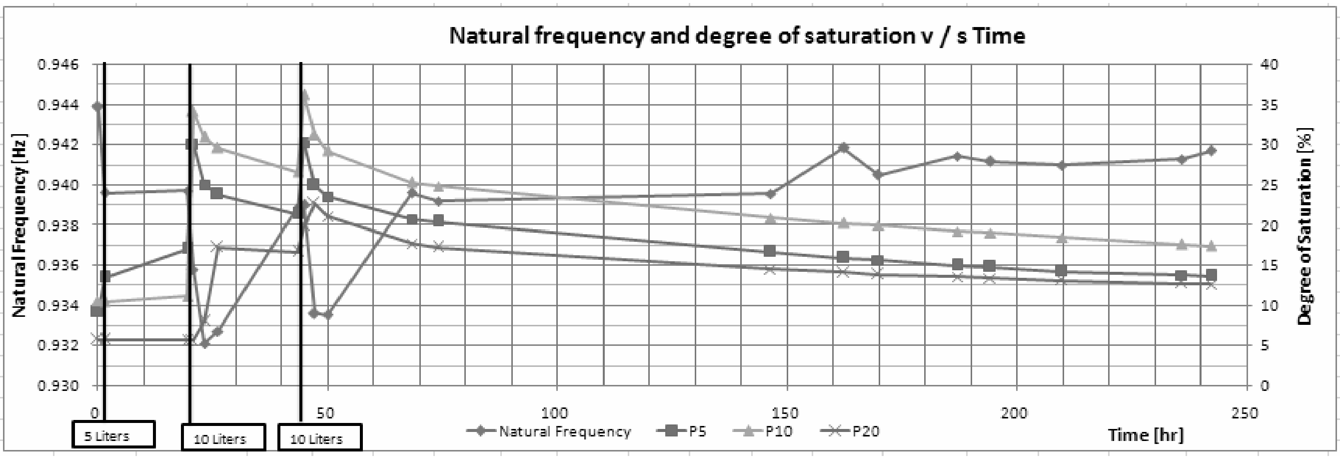

Figure 5. Natural frequency and degree of saturation at different depths for a period of 10 days

hours, and then it kept increasing slowly until stabilizing in a value close to 0.942, similar to the initial value of natural frequency. As long as the water content stabilizes, the natural frequency stabilizes as well, showing a good correlation.

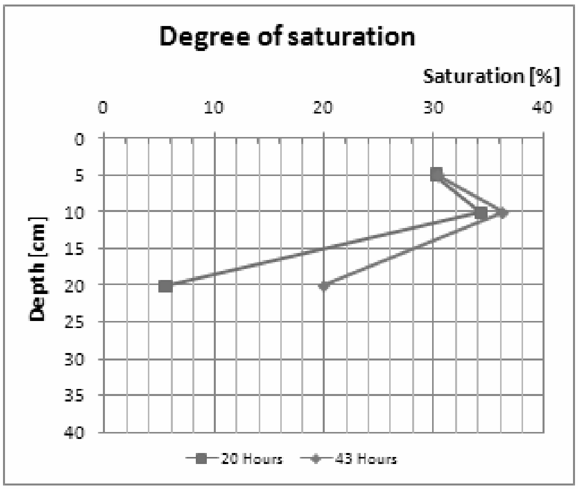

Figure 6. Degree of saturation profile two different times

4 CONCLUSIONS

This article presents preliminary results of a scale model test conducted at the Civil Engineering Laboratory at the University of Chile. The most relevant conclusions are:

- The results show a clear influence of the soil water content in the natural frequency of the soil-structure system.
- The records show that as soon as water was added to the model the natural frequency of the system decreased. It appears that any increment in the soil water content reduced the stiffness of the soil foundation, decreasing therefore the frequency of the system.
- There is a very good correlation between the natural frequency and the soil water content closer to the soil surface, which indicates in this case that the soil stiffness next to the foundation would tend to have a higher influence in the stiffness of the system.
- In the Millikan Library and the Chilean Construction Chamber building the natural frequency increased as soon as it rain, opposite to what happened in the scale model. The authors believe that the different nature of the soil had a direct effect in the responses; the real structures are located over grave deposits, while the scale structure was modeled on top of a fine silty sand deposit.
- This study confirms the effect of water in the natural frequency of soil-structure systems observe in real structure, showing for the very first time a correlation between natural frequency and soil water content profiles along the depth of a soil deposit.
- It is important to keep investigating the effect of climatic changes in the variations of dynamic parameters of the soil-structure system, in order to properly use the structural health monitoring technique and isolate the changes due to structural damages.

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