Bridge scour monitoring technique using the vibratory response of rods embedded in the riverbed

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Abstract

Local scour is a major risk threatening the stability and sustainability of bridges across rivers and in coastal areas. The main purpose of this paper is to propose a monitoring technique based on the dynamic response of rods embedded in the riverbed. First, extensive laboratory tests are conducted to investigate the effect of scour on the vibratory response of different rods in sand and in saturated clay soil. Secondly, a numerical finite element model is developed and validated with these laboratory tests. This model is then used to assess the effect of the added mass of water on the sensor. Finally, based on the numerical and experimental results, a simplified analytical cantilever model is proposed to correlate the dynamic response of the rods to the current scour depth.

Keywords: Bridge; Pier; Scour; Vibration; Exposed length; Equivalent cantilever; Monitoring.

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1. Introduction

Bridge scour is the erosive action of water carrying away sediments around bridge supports, namely piers and abutments. This phenomenon accounts for nearly 60% of bridge failures in the United States (Wardhana and Hadipriono, 2003). In France, the collapses of the Wilson Bridge in Tours (1978) and the St Louis Bridge on Reunion Island (2007) (see Fig. 1) are national examples of the damages caused by scour (Chevalier et al., 2014).

Fig. 1 Collapse induced by scour of the RN1 bridge on the St Etienne River, Reunion Island (Feb 2007)

In order to ensure the safety and stability of bridges, scour depth must be determined, not only during the design phase, but throughout the entire service life of the structure. To this end, on the one hand, many empirical equations were developed (Froehlich, 1988; Melville, 1997; Sheppard and Jr., 2006; Arneson et al., 2012; Sheppard et al., 2013). However, most of these equations are derived from flume tests on small scale models and tend to either overestimate or underestimate this value. On the other hand, the traditional approach of visual inspections of the structures may not reveal the real extent of this risk since scour takes place underwater. It is therefore crucial to develop continuous monitoring techniques to anticipate future damages and collapses.

2. Monitoring of scour phenomenon

Indeed, in order to address this risk, various monitoring techniques have been developed. The methods based on geophysical techniques such as radar (Gorin and Haeni, 1989; Millard et al., 1998; Anderson et al, 2007) and sonar (Lu Deng, 2010) were largely deployed on field in early days. However, those techniques suffered from high sensitivity to noise, difficulty in the results interpretability and the impossibility to use these techniques for continuous monitoring, especially during floods (Kong and Cai, 2016). For this purpose, new monitoring techniques have being proposed including the sliding magnetic collar (Lu et al, 2008), time-domain reflectometry (Yankielum and Zabilansky, 1999; Yu and Yu, 2009), fiber optic (Lin et al., 2005; Zarafshan et al., 2012) and vibration based techniques (Foti and Sabia, 2011; Zarafshan et al., 2012; Prendergast et al., 2013; Bao et al., 2017). Two distinct approaches have been proposed to deploy the vibration based techniques, monitoring the frequency of the bridge or the pier itself or monitoring the frequency of a rod sensor embedded around the pier.

Foti and Sabia, (2011) studied the effect of scour on a full bridge in Italy. The response of the bridge induced by traffic was recorded before and after the retrofitting of the scoured pier. The study concluded that scour caused a decrease of the frequency and induced abnormal modal shapes of the span supported by the scoured pier. After the retrofitting, both the frequencies and modal shapes became “normal”, meaning as they should be. Prendergast et al., (2013) investigated the feasibility of monitoring scour with an accelerometer placed on a single pile. The experimental tests were conducted using a single pile of 1.26 m pile placed in sand in the laboratory and a 8.76 m single pile on the field. His study concluded that scour causes a decrease of the first frequency, however no attempt was made to correlate the variation of the frequency to the current scour depth. Zarafshan et al., (2012) proposed to monitor scour with sensor rods. A fiber Bragg grating sensor was used to measure the frequency of the rods. In order to correlate the measured frequency to the current scour depth, a numerical model based on the Winkler theory of the soil was developed. The sensor was modeled as a beam and the soil as a series of independent linear springs. The stiffness of the springs was fixed when installing the sensor by measuring the frequency for different exposed lengths. The model was then used to identify the current scour depth: scour was modeled by the removal of the springs and the frequency of the sensor was calculated for each scour depth.

Therefore, there is a general agreement that vibration based methods can be used to detect scour, however,, some issues remain unsolved. In all the presented studies, the technique was tested in sand soil; the effect of the stiffness of the soil on the sensitivity of the frequency was not investigated. Secondly, the effect of water on the detected frequency was generally neglected. For sensor rods which are supposed to be completely immersed in water, this effect might be significant. Finally, the correlation between the current scour depth and the measured frequency in previous studies was mainly established using a numerical simulation.

The following paper tries to address the previous issues, by understanding the physical phenomena and developing a numerical model for beam-like structures embedded in soil and subjected to scour. This leads us to study the possibilities of monitoring scour with an instrumented rod embedded in the riverbed, which will call Scour-Depth Sensor (SDS) or even sensor hereafter.

First, rods of different geometries and materials were tested in the laboratory in sand at first, then in a soft clay soil to evaluate the effect of the stiffness of the soil. A numerical 3D model was then developed and validated with these tests. This numerical model was then used to compute the frequencies of the sensor completely immersed in water. Finally, based on the numerical and experimental results, a simplified cantilever model with a corrected exposed length was proposed to correlate the measured frequencies of the sensor to the current scour depth.

3. Laboratory validation of the scour-depth sensor

3.1. The experimental set-up

In order to investigate the effect of scour on the response of the sensor and evaluate its accuracy, extensive laboratory tests were performed. Rods of different materials, lengths and geometries were tested. Table 1 summarizes the characteristics of each rod. As shown, two lengths of the aluminum rods (L = 600 mm and L= 800 mm) were used in order to investigate the effect of the variation of the embedded length when the exposed length is kept fixed. Fig. 2 represents the circular aluminum rod.

Table 1 Characteristics of the rods

Test rod	Geometry	Outer diameter/Width (mm)	Thickness (mm)	Length (mm)	Young modulus (GPa)	Bulk density (kg/m^3)
Aluminum rod	Rectangular	19	2	600-800	59	2700
Aluminum rod	Circular	12	1	600-800	59	2700
PVC rod	Circular	20	2	800	3.5	1425

Scour was simulated by progressively increasing the exposed length of the sensor by 5 cm. For each scour depth, an impact was generated and the transient response of the rods recorded with an accelerometer placed on the top (T.Bao et al., 2017). Signal analysis, mainly Fast Fourier Transform, was then used to measure the first frequency of the rods for each scour depth.

The tests were performed in two type of soil: dry sand and a saturated clay soil. For each soil, repeatability tests were performed to evaluate the accuracy of the sensor. For each scour depth, the experiment was repeated three times in different locations of the soil. The details of the experimental tests carried out in each soil are detailed in the following sections.

3.2. Vibration tests in sand

The experimental set-up used for the test performed in sand is presented in Fig. 2. A thread is attached to the top of the rod and through a pulley; a known weight is attached to the other end. For each scour depth, the thread was cut generating an impulse force and inducing the vibration of the rod. The five rods (Table 1) were tested for different scour depths.

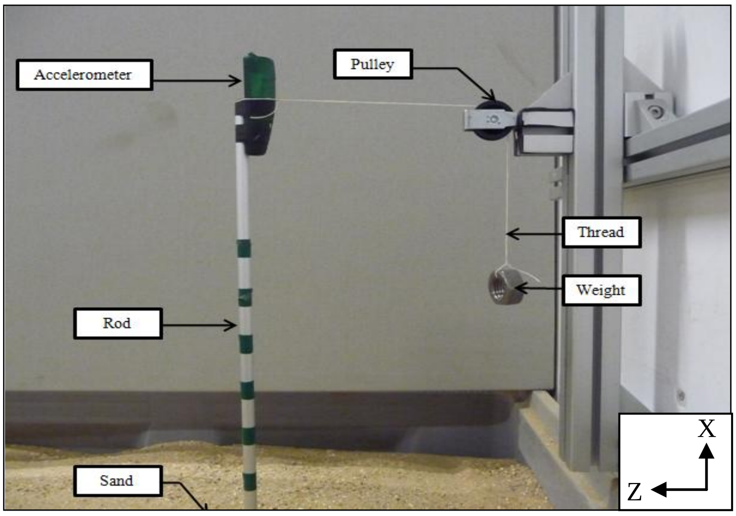

Fig. 2 Laboratory scour test in sand

The results of the tests are summarized in Fig. 3. As expected, for all the tested rods, the first frequency decreases with the increase of the exposed length. The sensitivity of the rods to scour was almost the same: for a variation of the exposed length from 40 cm to 65 cm, the variation of the frequency of the rods is 47 % for the aluminum circular rods, 53% for the PVC rod and 55 % for the rectangular one. The tests showed also high repeatability of the measurement with a variability of less than 5%.The testing showed that similar rods with two different embedded lengths and the same exposed length have the same first frequency.

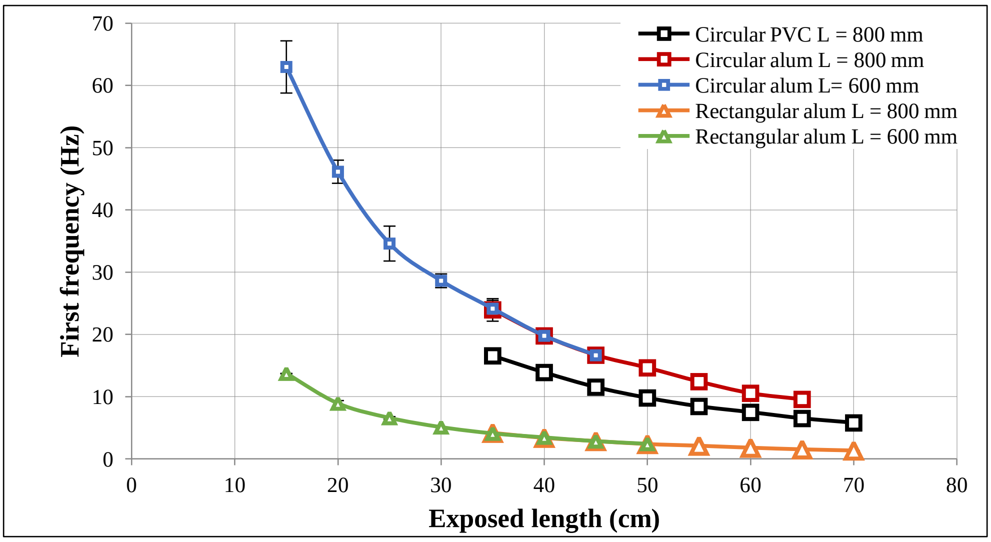

Fig. 3 Variation of the frequency with the exposed length in sand

3.3. Vibration tests in clay soil

In order to investigate the effect of the soil characteristics on the response of the sensor, the same tests have been performed in clayey soil. A saturated clay soil was prepared by progressively mixing 50 % of sand of Fontainebleau, 50% of clay of the kaolinite clay and water. The soil was then compacted by layers of 10 cm progressively to evacuate the air contained in the soil mixture. Two changes to the previous protocol were implemented. Firstly, the method of generating the impulse force was modified: the force applied to the rod with the previous protocol led to a plastic deformation of the clay soil. Instead, a series of impacts were applied to diminish the effect of the impulse force on the properties of the soil. Secondly, tests of the circular aluminium rods showed no vibratory response. The reason why these rods do not vibrate and show only rigid body motion (translation in the Z direction, see Fig. 2, which is the direction of the impact) is that the value of their relative stiffness $(EI)_{rod}$ is very high compared to the stiffness of the clay soil. As so, this soil does not ensure enough constraint to the circular aluminum rods which behave as a free-free beam.

The results of the rectangular aluminium rods and the circular PVC rod are summarized in Fig. 4. The tendency of the frequency of the rods in clayey soil is similar to the one in dry sand. However, the sensitivity of the rods to scour for a variation of the exposed length from 40 cm to 65 cm is lower; the variation of the frequency of the rectangular and PVC rods is 43 % and 45% respectively.

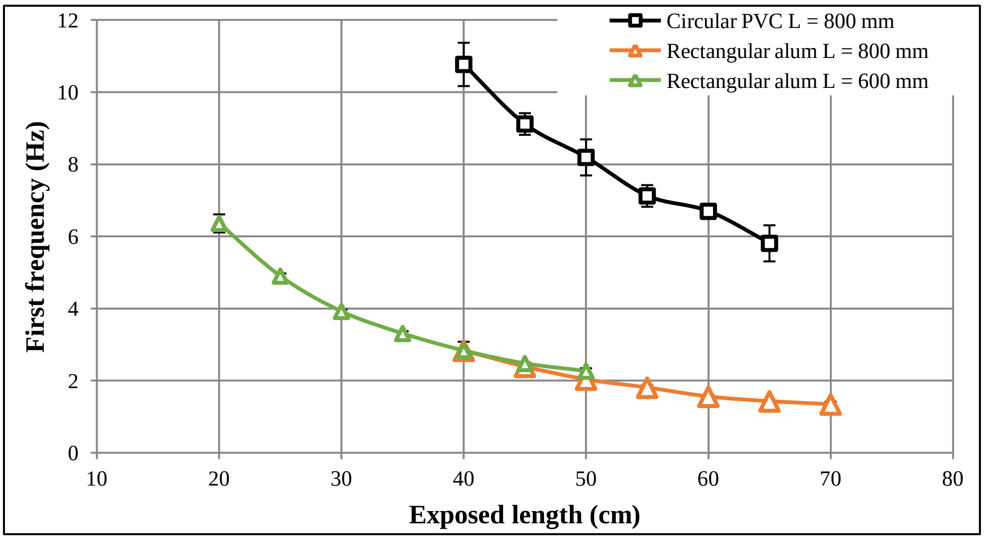

Fig. 4 Variation of the frequency with the exposed length in clay soil

In order to better understand how the frequency of the rods varies with the stiffness of the soil they are partially embedded in, the variation of the frequency with the embedded ratio of the rods (the embedded length normalized by the total length of the rod) in sand and clay soil are plotted in Fig.5. The embedded ratio decreases as scour develops.

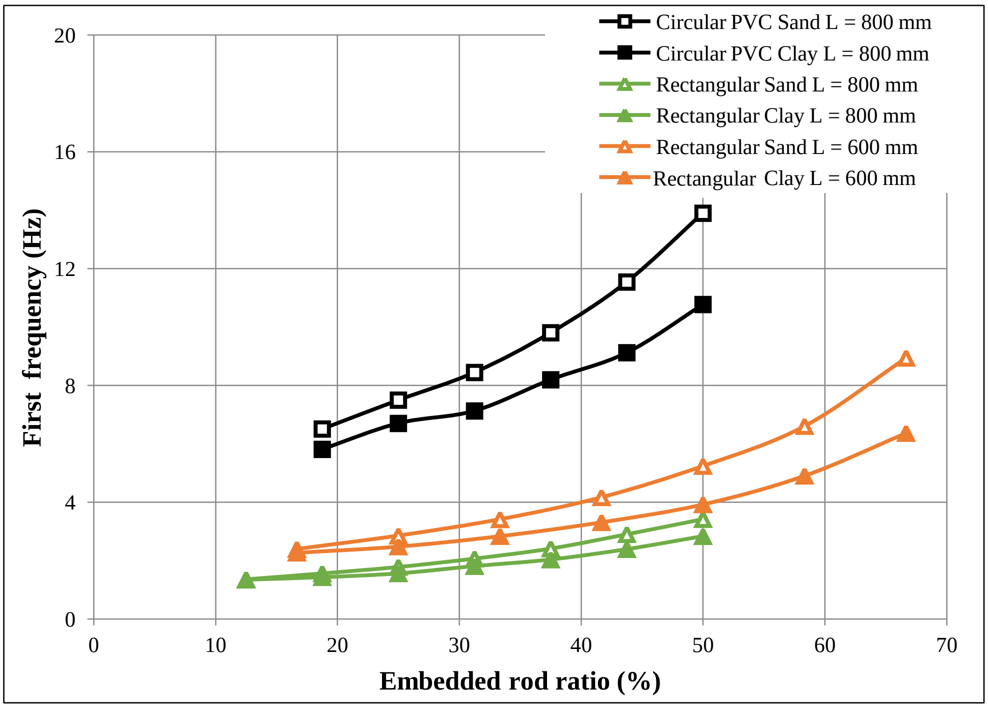

Fig. 5 Comparison of the frequency of the rods in different soil stiffness

The results show that for low embedded ratio, the frequency of the rods tends to be similar in both soils. However, as the embedded ratio increases, the frequency of the rod is explicitly affected by the stiffness of the soil it is embedded in.

4. Numerical model of the physical set-up

4.1. Numerical model validation

A numerical 3D finite element model of the experimental set-up (Fig. 2) was then developed using Code-Aster software to reproduce numerically the experimental test. The material properties of the rods, namely the Young modulus and bulk density, were obtained from laboratory tests. The Young modulus of sand was derived experimentally from the Menard modulus obtained from a mini pressuremeter test (Baguelin, 1978) conducted on the block of soil used in the laboratory. The behavior of both the soil and the rod were supposed linear elastic since the vibration induced only small deformations. The accelerometer was modeled as a nodal mass at the top of the rod. In the numerical model, the rod and the soil were bounded along the interface. The lateral faces of the soil were blocked against translation in the normal direction and the base was blocked in all directions. Scour was taken into account by the extraction of a scoured layer of soil. The first frequency was obtained directly from modal analysis.

The first frequencies of the five rods were computed for each scour depth and compared to the experimental frequencies. As it can be seen from Fig. 6, the numerical results are in good agreement with the experimental results for different geometries and materials of the rods without any readjustment of the model parameters

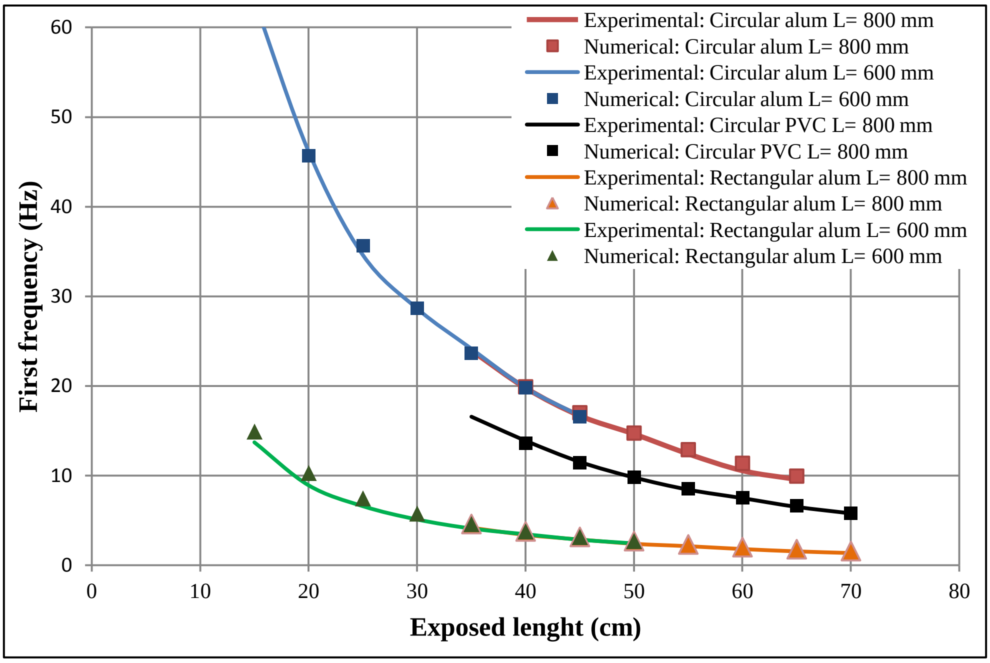

Fig. 6 Variation of the first frequency with exposed length in numerical and experimental tests

4.2. Introduction of the presence of water

The sensor is supposed to be driven in the soil around the pier and be partially or completely submerged in the water depending on the water level. As so, the previous validated model was used to investigate the effect of water on the frequency of the sensor. For each scour depth, the exposed length of the sensor was completely immerged in water. The numerical calculation was performed using only the circular aluminum rod. The “wet” frequencies were plot against the “dry” frequencies.

As shown in Fig.7, the “wet” frequencies of the rod are always lower. This was expected since the fluid acts as an added mass on the rod and thus decreases its frequency. The variation of frequency between the “dry” and “wet” condition was up to 10%. Therefore, for this kind of rod sensors, the effect of the fluid is not negligible and should be taken into account to accurately estimating the current scour depth.

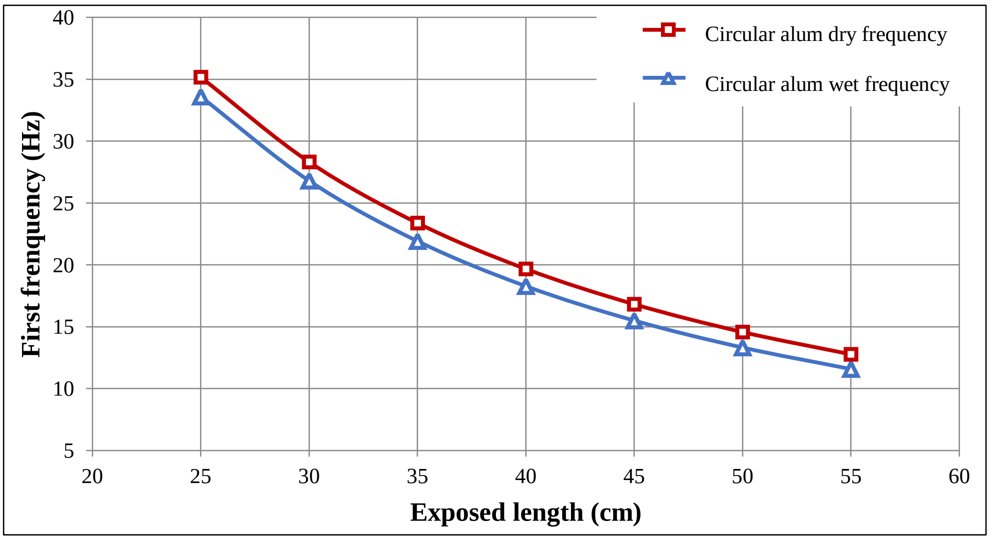

Fig. 7 Variation of the first frequency with scour in wet and dry conditions

5. Sensor calibration

The results of the laboratory tests in different soils detailed in Section 3 were plotted against the curve of the variation of the frequency of an equivalent cantilever. The theoretical frequencies f_{th} of the cantilever carrying a tip mass (Turhan, 2000) can be derived analytically giving Equation (1), where E is the Young modulus, I the inertia in the vibration direction, M the total masse of the "dry" cantilever, m the mass of the accelerometer and H the free length of the cantilever.

$$f_{th} = \frac{1}{2\pi} * \sqrt{\frac{3EI}{H^3 * (0.24M + m)}} \quad (1)$$

For each rod geometry and material, the frequencies of the equivalent cantilever are calculated and compared to the experimental frequencies of the rods in the soil. Figs. 8, 9 and 10 show that the experimental frequencies of the rods are translated against the theoretical frequencies of a cantilever with a fixed length H'. This means that the frequencies of the rods in the soil are identical to the frequencies of a cantilever with a free length equal to the exposed length of the rods increased with the "correction" length H'. This length varies with the rod geometry, material and the soil type. Table 2 summarizes the values of the "correction" length H', for different types of rods and soils.

Table 2 Values of the correction length of the equivalent cantilever

Test rod	Geometry	Correction length in sand (cm)	Correction length in clay (cm)
Aluminum rod	Rectangular	4.8	11
Aluminum rod	Circular	8.8	Not tested
PVC rod	Circular	4.6	11

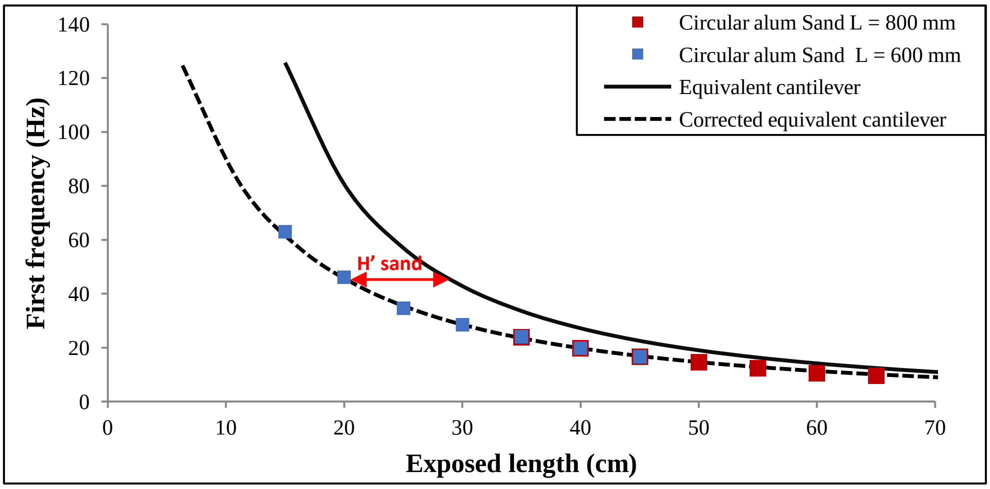

Fig. 8 Equivalent cantilever models of the circular aluminum rods in sand

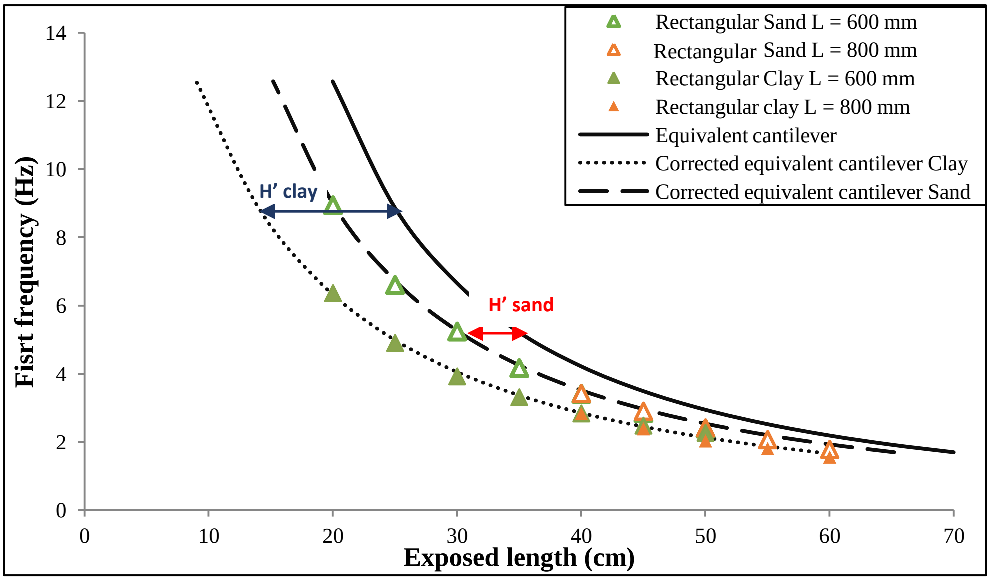

Fig. 9 Equivalent cantilever models of the rectangular aluminum rods in sand and clay soil

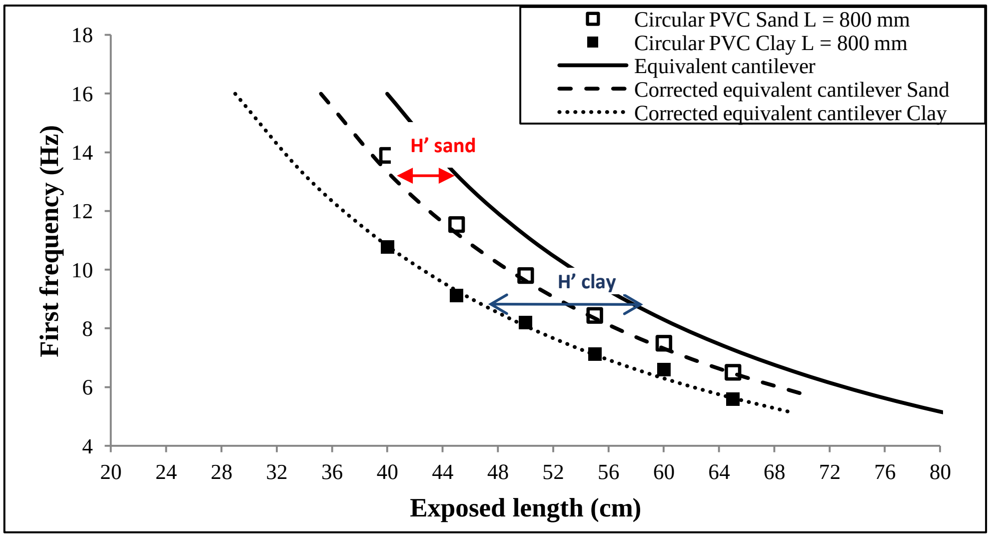

Fig. 10 Equivalent cantilever models of the circular PVC rods in sand and clay soil

Since the sensor will be immersed in water which causes the decreases of the measured dry frequencies, the validity of the cantilever model has to be verified. For this propose, the calculated wet frequencies of the circular rod presented in Fig. 7 were compared to the frequency of an immersed cantilever obtained from Equation (2) where M_a is the added mass of the fluid.

$$f_{imm} = \frac{1}{2\pi} * \sqrt{\frac{3EI}{H^3 * [0.24(M + M_a) + m]}} \tag{2}$$

Fig. 11 presents the corrected equivalent cantilever model of the circular rod in dry and wet conditions. It can be seen that when comparing the "wet" frequencies of the rod to the frequencies of "wet" cantilever model, the curves are shifted with a constant length H'_{wet}=8cm. The cantilever model is therefore applicable in immersed condition.

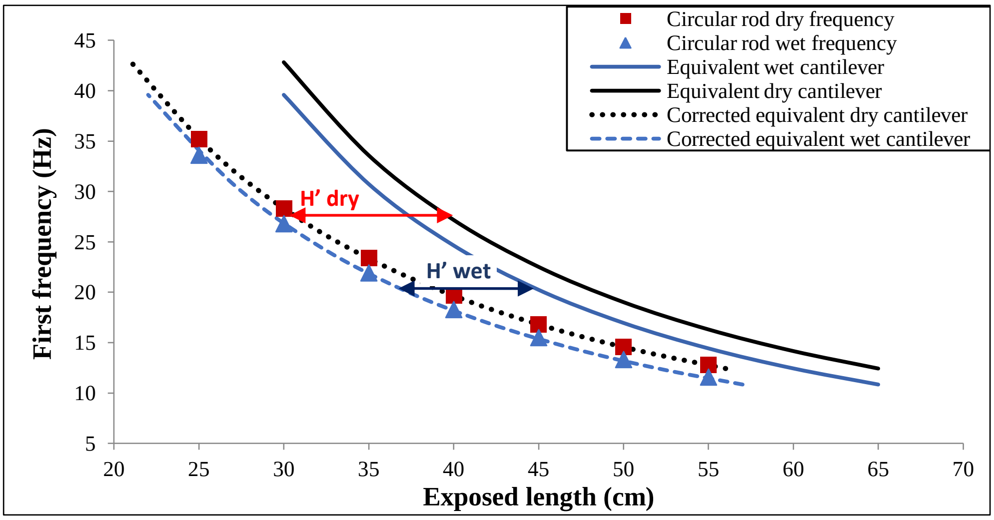

Fig. 11 Equivalent cantilever of the circular rod in dry and wet conditions

6. Summary and conclusions

Scour is a major risk threatening the safety and stability of bridges. Determining the current scour depth is a major challenge: many previous monitoring techniques are not very efficient during floods when scour reaches its peak. The vibration technique seems to be a promising approach for a continuous monitoring of scour around piers and abutments. The reported study proposes to monitor scour by means of rods partially embedded in the riverbed. Extensive laboratory tests were performed to evaluate the effect of scour on the frequency of different sensor geometries and materials. The effect of the stiffness of the soil was also investigated: dry sand and a soft clay soil were used. The results show that the frequency is sensitive to scour in both soils, however the sensitivity of the sensor decreases with the stiffness of the soil it is embedded in. A 3D numerical model was developed and validated. It was then used to investigate the effect of the immersed condition on the frequency of the sensor. The results show that the effect of the added mass is not negligible and should be taken into account for accurate measurement of scour depth. Finally, a simplified cantilever with an increased length was proposed to correlate the exposed length of the sensor to the measured frequency and thus an estimation of the current scour depth around piers. Future research will focus on implementation of the proposed monitoring technique on field.

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