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TECHNICAL NOTE

Performance of Impulse Response Testing on Prismatic Members with Intermediate Joints

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ABSTRACT: Nondestructive Testing (NDT) methods have extensively been used to assess the conditions of civil infrastructure in the recent decades. Among various NDT techniques, Impulse Response (IR) has a vast application due to its simplicity and low cost. However, factors such as reflections from changes in impedance along the investigated members can adversely influence the success of the method. Numerous numerical and experimental studies have already been performed to evaluate the effect of change in mechanical impedances such as bulging, necking and similar anomalies. In this study, the effect of the presence of joints connecting the investigated members to other members, as another source of impedance change, is demonstrated. A three-story steel-concrete composite column of a building was selected for testing and IR tests were conducted. The obtained mobility graphs were clear, and the height of the column was easily measured with an acceptable error. The results of this study show that although the joints located between the top and bottom of the tested member are sources of change in mechanical impedance, they do not result in concealing the resonant frequencies from the wave reflected from the bottom of the member. Thus, IR method seems to be applicable in determining the length of prismatic members with intermediate joints such as piles of unknown bridge foundations with bracing and columns of buried buildings.

Keywords: Bridge, Building, Foundation, Impulse Response, Pile.

1. Introduction

Nondestructive Testing (NDT) methods have been developed and utilized in the past decades to assess the condition of civil infrastructure (Coe et al., 2013; Rashidyan et al., 2016, 2017, 2019a,b). Among various NDT methods, Impulse Response (IR) is an economical technique with a wide range of applications including evaluating the integrity of constructed drilled shafts as well as characterizing unknown bridge foundations for which there are no or limited information available.

In performing Impulse Response tests, longitudinal sonic waves are created by hitting the top of the deep foundation using a hammer as indicated in the IR test setup in Figure 1a (Hertlein and Davis, 2007). Upon striking, a longitudinal wave with velocity *v*

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is generated along the pile. The generated wave travels down with velocity v and reaches to the bottom of the pile. At this moment, due to the change in mechanical impedance of the materials, a part of the wave energy will be transmitted through the interface to continue traveling in the soil (transmitted wave) and the remainder will be reflected at the interface toward the top of the pile. The impedance change can be from change in pile cross section, material density or pile-soil interaction.

In this method, using either an accelerometer or a geophone attached to the top surface of the pile (see Figure 1a), the velocity signal from the generated wave is captured. Using the Fast Fourier Transform analysis, the frequency content of the obtained strike and velocity signals are extracted. The ratio of the converted velocity and force called mobility will be determined. An example of a diagram of mobility -frequency is shown in Figure 1b. When the wave lengths of the created sonic waves are greater than the diameter of the pile, resonant frequencies will be distinguishable as shown in Figure 1b (Hertlein and Davis, 2007). The resonant frequencies depend on the length of the tested pile and the velocity (v) of the generated sonic wave. The pile length can be determined as:

$$L = \frac{v}{2 \times \Delta \mathrm{f}} \tag{1}$$

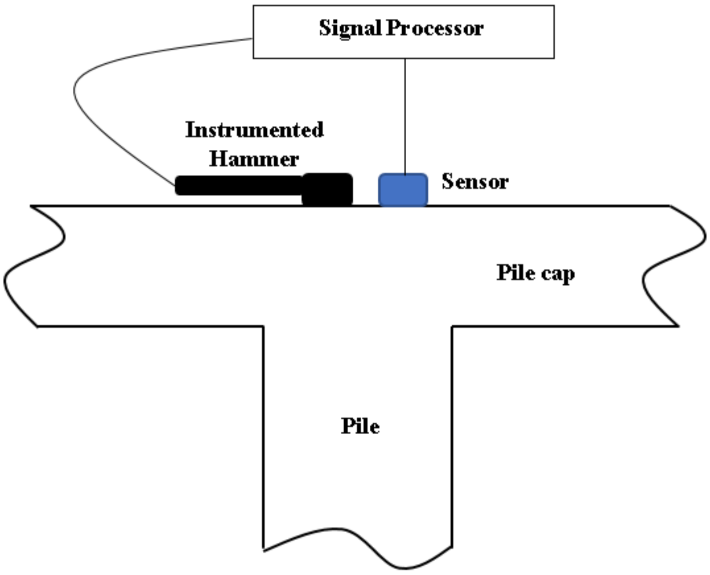
where v and Δf: are the velocity and difference between resonant frequencies, respectively.

The IR method was initially used to assess the integrity of foundations in 1960s in France. The method was then utilized by many researchers leading to more available information regarding factors influencing the performance of the method. Finno et al. (1997) and Finno and Gassman (1998) utilized IR technique to assess the integrity of drilled shafts with accessible top. They showed that in such piles, the ratio of length to diameter, the ratio of the shear wave velocity of the soil to the velocity of the propagated wave in pile, and the layered soil influenced the results of IR tests. Baxter et al. (2004) showed that the IR method was challenging when the top of the pile was inaccessible due to the presence of a the pile cap. This was in accordance with the observations of Wu et al. (2015) who reported that the depth of the pile could not be determined.

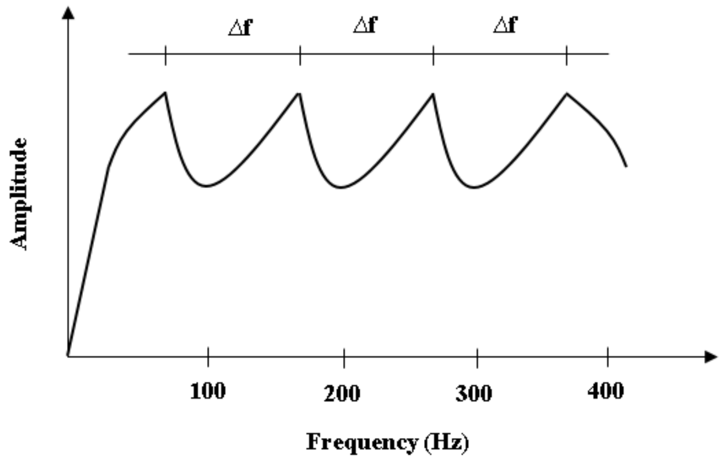
Aside from determining the depth of piles with and without caps, IR method has been utilized to assess drilled shafts with anomalies. Briaud et al. (2002) used IR method to study drilled shafts and reported the success rate in integrity assessment of the investigated piles for anomalies such as bulging, necking, soft bottom and mud cake. Ni et al. (2011) proposed formula to determine the size of the anomalies in drilled shafts. They showed that the depth of the anomaly and stiffness were major parameters influencing the results.

In addition to piles, the applicability of IR method was also studied to determine the length of prismatic geotechnical objects such as soil nailing. Liao et al. (2008) carried out tests on soil nails. Their results indicated that the stiffness ratio of the soil nail to the bond material were major parameters affecting the success of method. More information regarding the applicability of IR tests on other civil infrastructure related members can be found in Sajid and Chouinard (2019).

As stated above, previous studies have shown that factors such as presence of pile cap, change in impedance (from anomalies, defects and so on) along the drilled shaft, and the surrounding soil can affect the IR tests results. In the current study the performance of IR method were investigated in cases where other sources of change in impedance exist along prismatic members. The targeted changes are from members that are connected to the investigated member at different points along the member. Such changes in mechanical impedance can be for instance from horizontal and longitudinal bracings connected to piles in bridge foundations. An example of a bridge foundation composed of piles and bracing is indicated in Figure 2. To achieve the goals of this research, IR tests have been conducted on a steel-concrete composite column with two beam-column joints between the top and bottom of the column and the effect of the existence of such changes in impedance on the success of IR tests is investigated.



(a)



(b)

Fig. 1. a) Schematic of the IR test set-up and; b) Consecutive resonant frequencies on a typical mobility graph (Hertlein and Davis, 2007)

Fig. 2. An example of a bridge foundation composed of piles and bracing

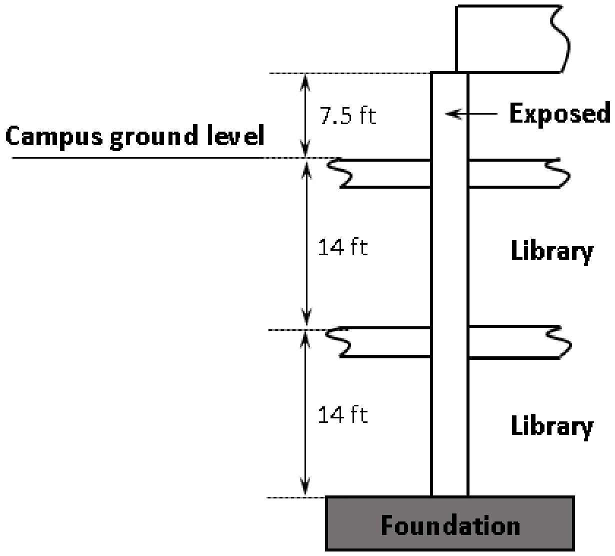
2. Methodology

IR tests were performed on a three-story steel-concrete composite column. The investigated column composed of a W14 × 90 steel section buried in a 20 inch concrete casing. The elevation, cross section view, and exposed part of the column are shown in Figure 3a,b,c, respectively. Two stories of the column are located below ground level and the third floor is exposed as indicated in the Figure 3a. The exposed part is constructed for aesthetic purposes and provides support for a shed structure made of light textiles. A photo of the exposed part is indicated in Figure 3b.

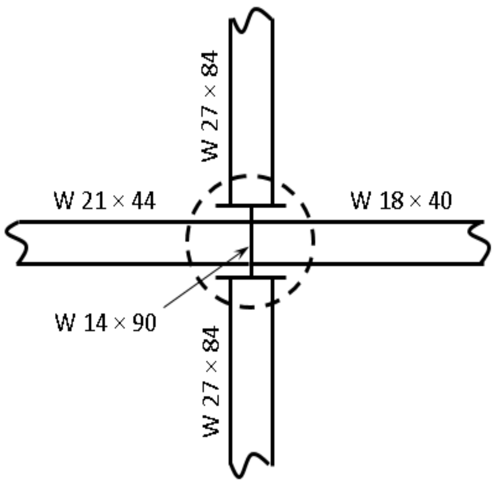
The IR tests were performed based on the following procedure:

2.1. Test Setup

The accelerometer was mounted vertically at the top of the column and vertical blows at top was applied. The IR test configuration is shown in Figure 4.



(a)



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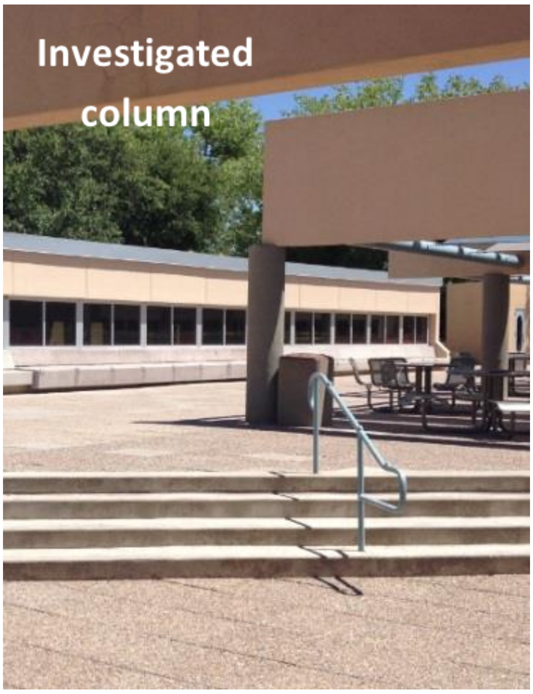


(c)

Fig. 3. The concrete column of centennial library on UNM campus: a) Elevation, b) Cross section plan and; c) Exposed part

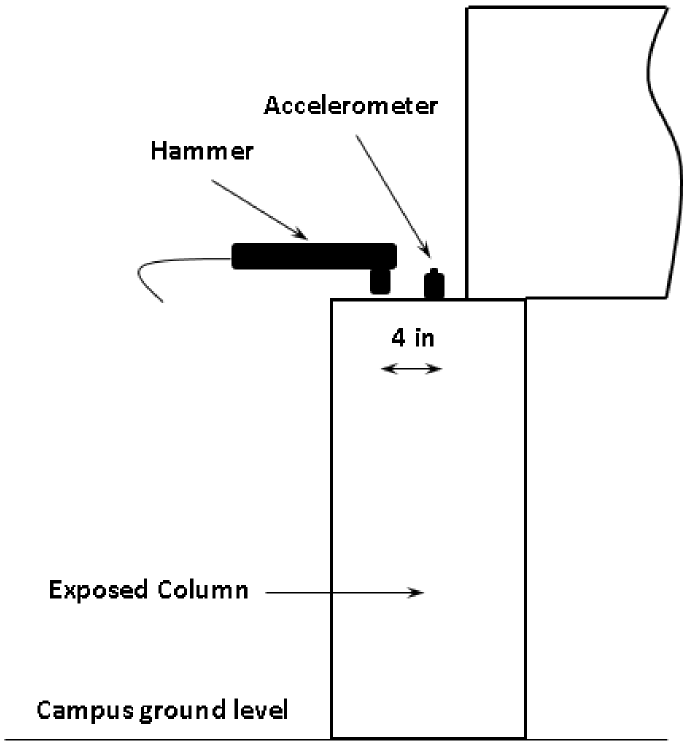


Fig. 4. IR test setup for the steel-concrete composite column of centennial library on UNM campus

2.2. Hardware Assembly and Perform Tests

The utilized equipment was in accordance with ASTM D5882-07-2013 (American Society for Testing Materials, 2013) and ACI 228.2R-13 (American Concrete Institution, 2013). It consisted of a Freedom Data PC platform, an accelerometer, a 3-lb instrumented hammer and various heads. The hammer heads were hard, medium hard, and medium soft with contact durations of approximately 1200, 2400, and 3600 μs respectively. The hammer tip type used in each test is indicated in Table 1.

The height of the investigated column was determined using the mobility graphs obtained from the accelerometer. Since the steel profile W14×90 occupies approximately 8 percent of the cross section of the column, the entire member is assumed as a solid concrete member. Therefore the speed of the propagated wave in concrete was assumed 13000 ft/s pursuant to literature (Kurup and Kumar, 2017; Murasaka, 2015). Once the heights were measured, they were compared to the actual height of the column. The height of the column is 35.5 ft as indicated in Figure 3.

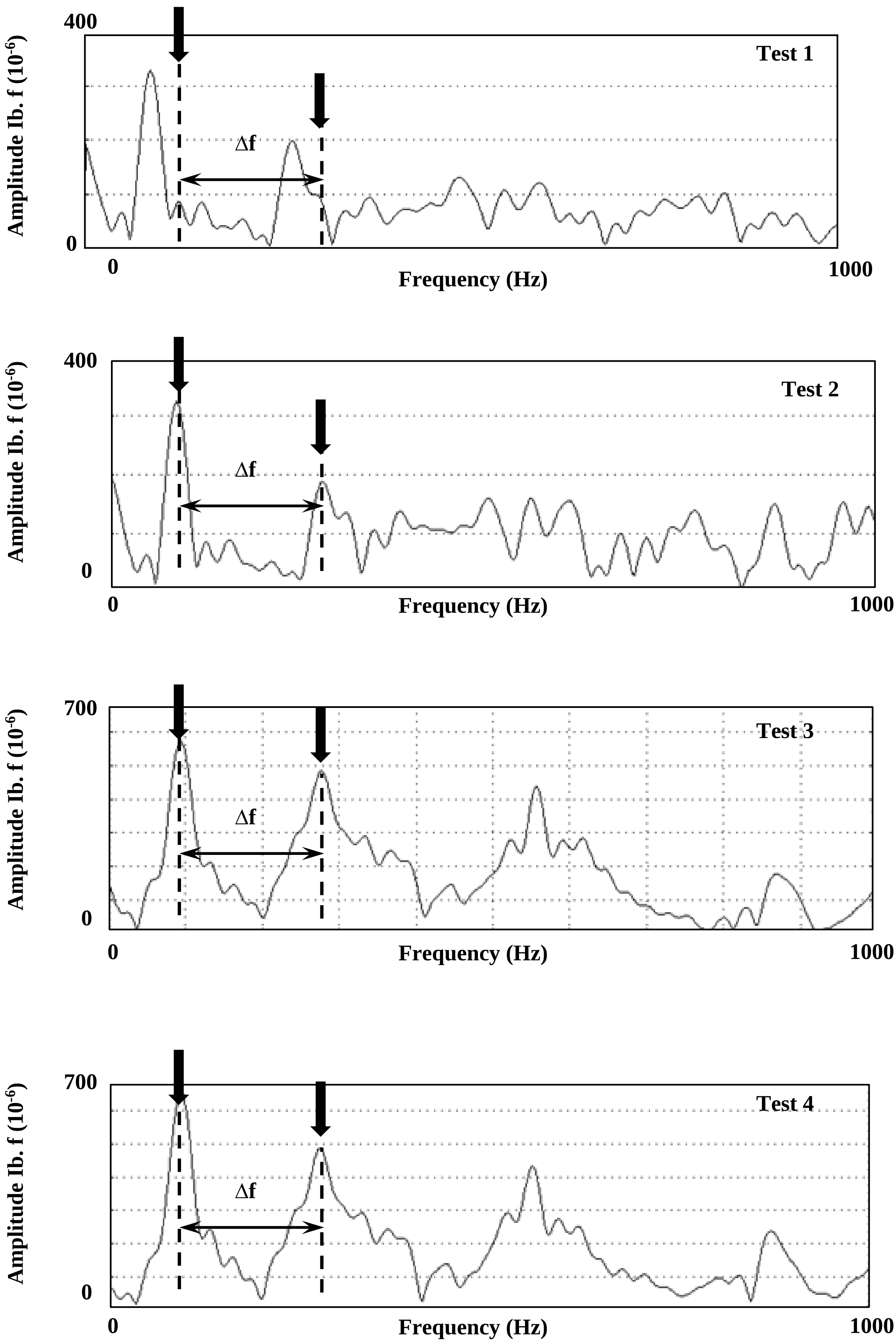
2.3. IR Testing Results

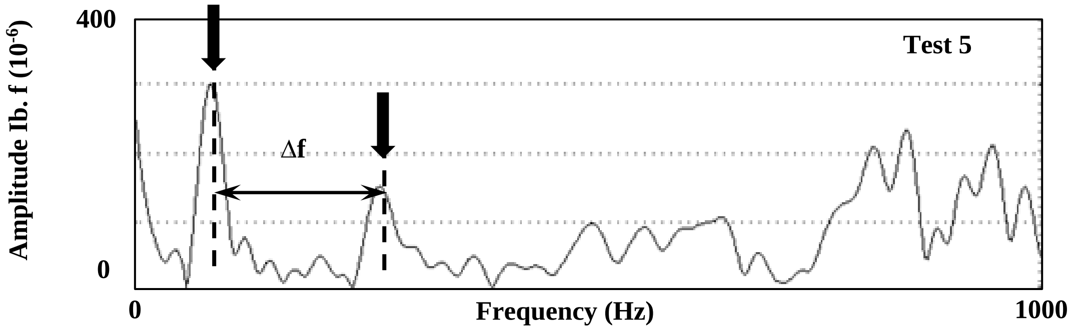
Twelve IR tests were performed with various hammer heads as indicated in Table 1. The height of the column was determined by measuring the distances between the consecutive resonant frequencies and substituting them in Eq. (1). The mobility graphs for all the twelve performed IR tests are shown in Figure 5.

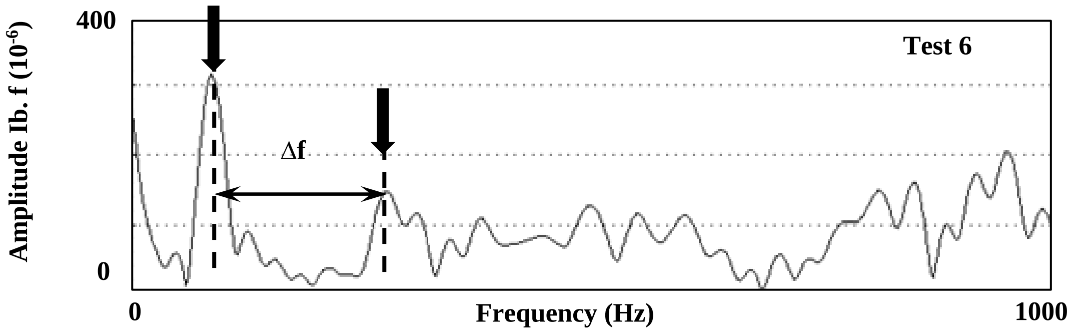
The graphs shown in Figure 5 present clear first and second resonant frequencies for all tests conducted by various types of hammer tips. The resonant frequencies have large amplitudes which distinguish them among a wide range of frequencies. Therefore, the differences between the two consecutive resonant frequencies can be measured easily. The measured resonant frequency differences and the calculated depths are summarized in Table 2. The heights are calculated using Eq. (1).

The results indicated in Table 2 show that the estimated heights of the column were consistent with the actual dimension of the column. The errors are less than 5%.

The results show that although there are joints between the top and bottom of the column, the reflections from such beam to column joints may not conceal the echoes from the bottom of the column on the mobility graphs. Thus, IR method seems to be a useful method in determining the height of such structural elements.




400
0
Amplitude Ib. f (10^-6)
Test 5
Δf
0
Frequency (Hz)
1000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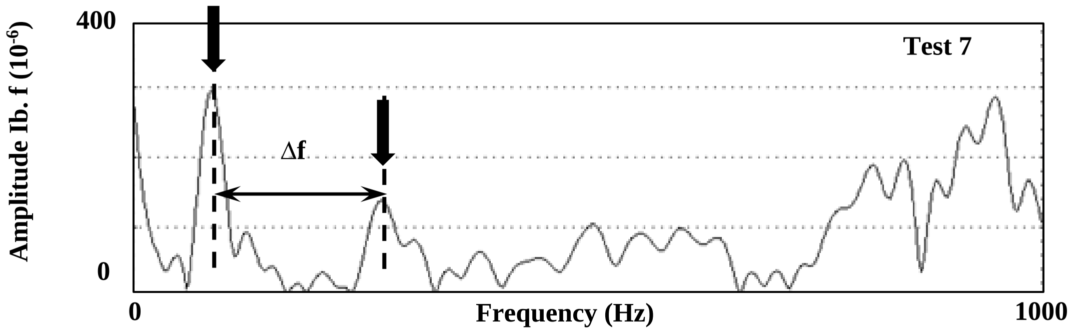
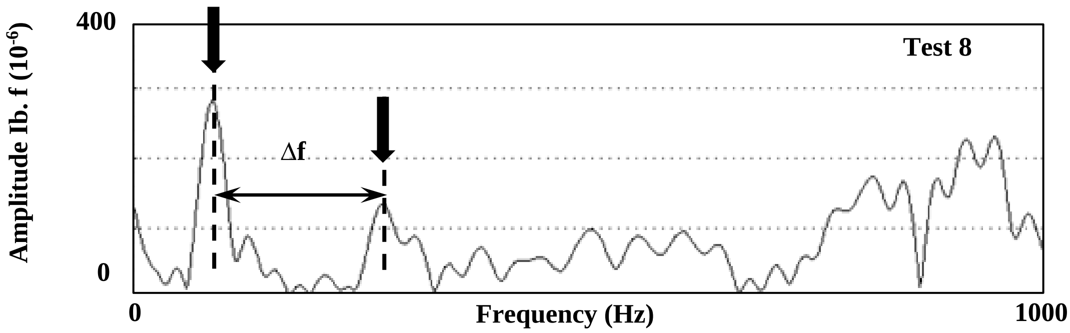
0
Amplitude Ib. f (10^-6)
Test 6
Δf
0
Frequency (Hz)
1000


400
0
Amplitude Ib. f (10^-6)
Test 7
Δf
0
Frequency (Hz)
1000


400
0
Amplitude Ib. f (10^-6)
Test 8
Δf
0
Frequency (Hz)
1000

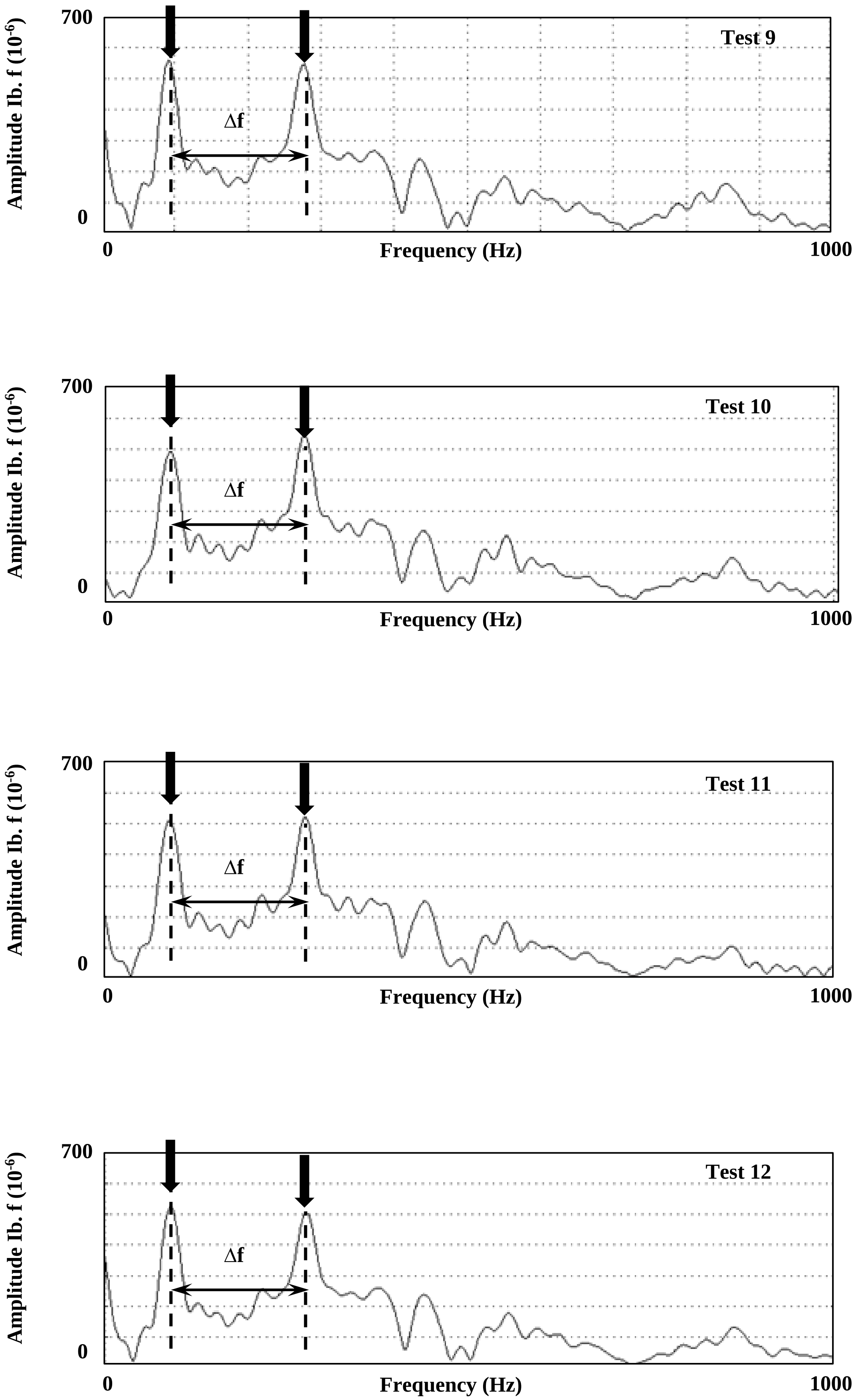


Fig. 5. The mobility graphs for all performed IR tests 1 to 12

Table 1. Characteristics of IR tests on the concrete column of centennial library on UNM Campus

Test No.	Hammer tip	Approximate duration of strike (μs)
1 to 4	Hard	1200
5 to 8	Medium-hard	2400
9 to 12	Medium-soft	3600

Table 2. The measured resonant frequency differences and the calculated depths and estimated errors

Test No.	Hammer tip	Δf (Hz)	Measured H (ft)	Estimated error (%)
1	hard	188	34.6	-2.6
2	hard	191	34.0	-4.1
3	hard	183	35.5	0.1
4	hard	183	35.5	0.1
5	medium-hard	178	36.5	2.9
6	medium-hard	191	34.0	-4.1
7	medium-hard	188	34.6	-2.6
8	medium-hard	188	34.6	-2.6
9	medium-soft	186	34.9	-1.6
10	medium-soft	183	35.5	0.1
11	medium-soft	186	34.9	-1.6
12	medium-soft	183	35.5	0.1

3. Conclusions

IR testing is a versatile NDT method to characterize existing infrastructure such as unknown bridge foundations. In performing IR tests, many factors affect the quality of the received signals. The change of mechanical impedance along the investigated object is among major factors which can affect the success of the method. Previous studies have investigated the performance of the method in the presence of changes such as bulging, necking and similar anomalies. In the current study another source of impedance change is investigated. In our case, the change in impedance is provided by connecting other structural members to the investigated member at joints located between the top and the bottom of the member.

To study the success of IR tests in such cases, twelve tests were performed on a three-story composite column of a building. The IR tests were performed with various common hammer heads. The mobility graphs show clear first and second resonant frequencies for all the tests conducted by various types of hammer tips. The resonant frequencies had large amplitudes which recognized them among other existing frequencies. Therefore, the differences between the two consecutive resonant frequencies and consequently the height of the column were measured easily with an error less than 5%. The results of this study show that although the joints located between the top and bottom of the column are sources of change in mechanical impedance, the reflections from such points of change in impedance do not conceal the resonant frequencies from the wave reflections from the bottom of the member.

Thus, the IR method seems to be applicable in measuring the entire height of structural elements with joints existing along the member. Such joints can be found in bridge foundations with bracings connected to the piles as well as in buried building with beam-column joints. It should be noted that our study is conducted based on a simple column with a specific geometrical characteristic. More future theoretical and practical investigations is proposed to reveal more aspects of the difficulty such as the influence of the soil, the size of the elements connected to the piles and columns, the ratio of the steel to concrete and the quality and characteristics of the joints.

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