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The effects of scour depth and riverbed condition on the natural frequencies of integral abutment bridges

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Abstract. The effects of foundation scour depth and riverbed condition on the natural frequencies of a typical cross-river integral abutment bridge have been studied. The conventional operational modal analysis technique has been employed in order to extract the modal properties of the bridge and the results have been used in the Finite Element (FE) model updating procedure. Two tests have been carried out in two different levels of water and wet condition of the riverbed. In the first test, the riverbed was in dry condition for two subsequent years and the level of water was 10 meter lower than the natural riverbed. In the second test, the river was opened to water flow from the upstream dam and the level of water was 2 meter higher than the natural riverbed. The results of these two tests have also been used in order to find to what extend the presence of water flow in the river and saturation of the surrounding soil affect the bridge natural frequencies. Finally, the updated FE model of the bridge has been applied in a series of parametric analyses incorporating the effect of piles' relative scour depth on the bridge natural frequency of the first four vibration modes.

Keywords: bridge; natural frequency; modal analysis; scour depth

1. Introduction

Many of bridges are located over seasonal rivers and the level of water as-well-as the riverbed condition may vary in different times. Many of these bridges suffer from foundation scour which need to be monitored (Loh *et al*. 2014, Azhari *et al*. 2015). To quantify the effects of these phenomena on the bridge dynamics, three typical questions are to be resolved as follows:

- How much the presence of water around the bridge piers and foundation together with the seasonal condition of rivers affect the natural frequencies of bridges?
- In the case of scour of foundation or pile system of a bridge pier, is there any meaningful relation in between the scour depth and bridge natural frequencies?
- How much the soil type affects the dynamic response of bridges?

For such situations, it has been accepted that because of the natural and physical complexity of soil-water-foundation interaction, no sufficiently and reasonably accurate results is found by using

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mathematical or FE models alone. In order to find reasonable responses to these questions, actual full scale dynamic tests of bridges of similar condition in parallel with supporting numerical models are usually used.

To the best knowledge of the authors, no extensive studies on the effect of the scour depth and riverbed condition on the modal characteristics of integral abutment bridges have been reported in the published literature. For instance, Chen and Gou conducted numerical analyses on buried foundation in scour condition and showed that the flexibility of foundation-soil system increases due to scour which reduces the bridge natural frequency and the associated damping ratios (Chen and Gou 2012). Alipour and Shafeie showed that by increasing the scour depth of bridges, the transverse and vertical load carrying capacity of bridges reduces which increases the seismic vulnerability of the bridge (Alipour and Shafeie 2012). Feng and Huang proposed a mathematical relationship between the natural frequency and scour depth of bridges through FE modeling and genetic algorithm (Feng and Huang 2013).Through FE analysis of Kujang Bridge, Zhang *et al.* showed that variation of the natural frequency of bridges can be ignored for lower values of scour depth (Zhang *et al*. 2013). Prendergast and Gavin compared the results of both the analyses of numerical model of a bridge and its vibration tests in scour condition of the foundation-pile system (Prendergast and Gavin 2014). Ju developed a FE model of a bridge in parallel with a validation test to find its natural frequencies with soil–fluid–structure interactions and showed that the effect of water may be neglected in the bridge’s natural frequencies. He concluded that if the scour depth to be over the pile cap, variations of the natural frequency with scour depth is more obvious (Ju 2013). Prendergast et al. examined the effect that scour has on the frequency response of a driven pile foundation system using laboratory and field testing. They showed that there is a clear reduction in the natural frequency of the pile as the severity of scour increases. They concluded that by combining state-of-the-art geotechnical techniques with relatively simple FE modeling approaches, it is possible to accurately predict the natural frequency of the pile for a given scour depth (Prendergast *et al.* 2013). Foti and Sabia reported a case history of assessment and monitoring with dynamic tests for a bridge affected by scouring and subjected to retrofitting. They used two different approaches measuring traffic-induced vibrations as potential tools for monitoring foundation scour (Foti and Sabia 2011). Elsaid and Seracino assessed possible using of horizontally-displaced mode shapes and any change in the dynamic flexibility features to identify scour from the response of bridge superstructure. They showed that the vertically-displaced mode shapes are not sensitive to scour and the natural frequencies of significant horizontally-displaced mode shapes decrease as the magnitude of scour increases. They concluded that changes in the flexibility-based deflection can be used to detect the location of scour (Elsaid and Seracino 2014).

In the present work, using ambient vibration tests and FE modeling of a typical river crossing integral abutment bridge, the effects of the presence of water flow around the bridge piers and the scour depth on the bridge’s natural frequencies have been studied.

2. The bridge under study

The bridge under consideration is a two span RC integral abutment bridge located in the Isfahan-Ziar highway over the Zayanderood River. There are two separate bridges of similar geometry for each direction. The first bridge, constructed in 1980, is a simply supported bridge of pre-cast concrete I-girder with a wall type intermediate pier and shallow foundation. The deck of the bridge is supported over middle pier and abutments through elastomeric bearings. On the other hand, no structural connection in between the superstructure and substructure exists. Because of the support condition of this bridge, it is predicted that no significant effect exists from foundation scour and presence of water flow on the natural frequencies of the superstructure of the bridge. Therefore, this bridge has not been studied here.

The second bridge, constructed in 2012, can be regarded as the widened part of the later bridge. The bridge is a joint-less continuous span bridge of pre-cast concrete I-girder with integral connection of the deck to the wall type side abutments and pile-column intermediate pier. The pier composed of three circular RC columns and a rectangular cap beam to form a framed bent of pile-column type. The main cause of selecting this bridge for the present study is the integrity of the superstructure and substructure connection. On the other hand, because of the boundary conditions and integrity of the deck-pier-pile system, it is predicted that any changes to the scour depth or riverbed condition can affect the natural frequencies of the bridge superstructure.

A side view and an underneath photo of this bridge are shown in Fig. 1. The general plan view, elevation and the deck section of the bridge are shown schematically in Fig. 2.

2.1 Modal tests

The tests have been carried out in different conditions of the riverbed from the viewpoint of the presence of water flow around the piers. The first stage of the modal test of the bridge has been done in during the passage of the normal traffic (ambient vibration test) in dry condition of the riverbed, as can be seen from Fig. 1. It should be noted here that the first test has been carried out in 2012 when the construction phase of the bridge had been finished and the bridge was ready to open to traffic of the new road. Also, because of the dry condition of the river for more than two years from 2010 to 2012, the bridge had not been experienced presence of water flow before doing the first test. At that time, the level of underwater was more than 10 meter below the riverbed.

The test has been carried out with the use of 12 tri-axial accelerometers and a 36-channel dynamic data logger with a sampling rate of 200 Hz in two consecutive arrangements (Fig. 3). One accelerometer was used in fixed position as the reference sensor (noted by S4 in Fig. 3). The accelerometers employed in the test were accurate to $\pm$0.001 g. The sensors have been located symmetrically with respect to the longitudinal and transverse axes of the bridge in order to obtain the mode shapes as clearly as possible. Duration of the test for data collection has been selected to be 30 minutes.

Fig. 1 Two photos of the bridge under consideration. The dry condition of the riverbed is shown

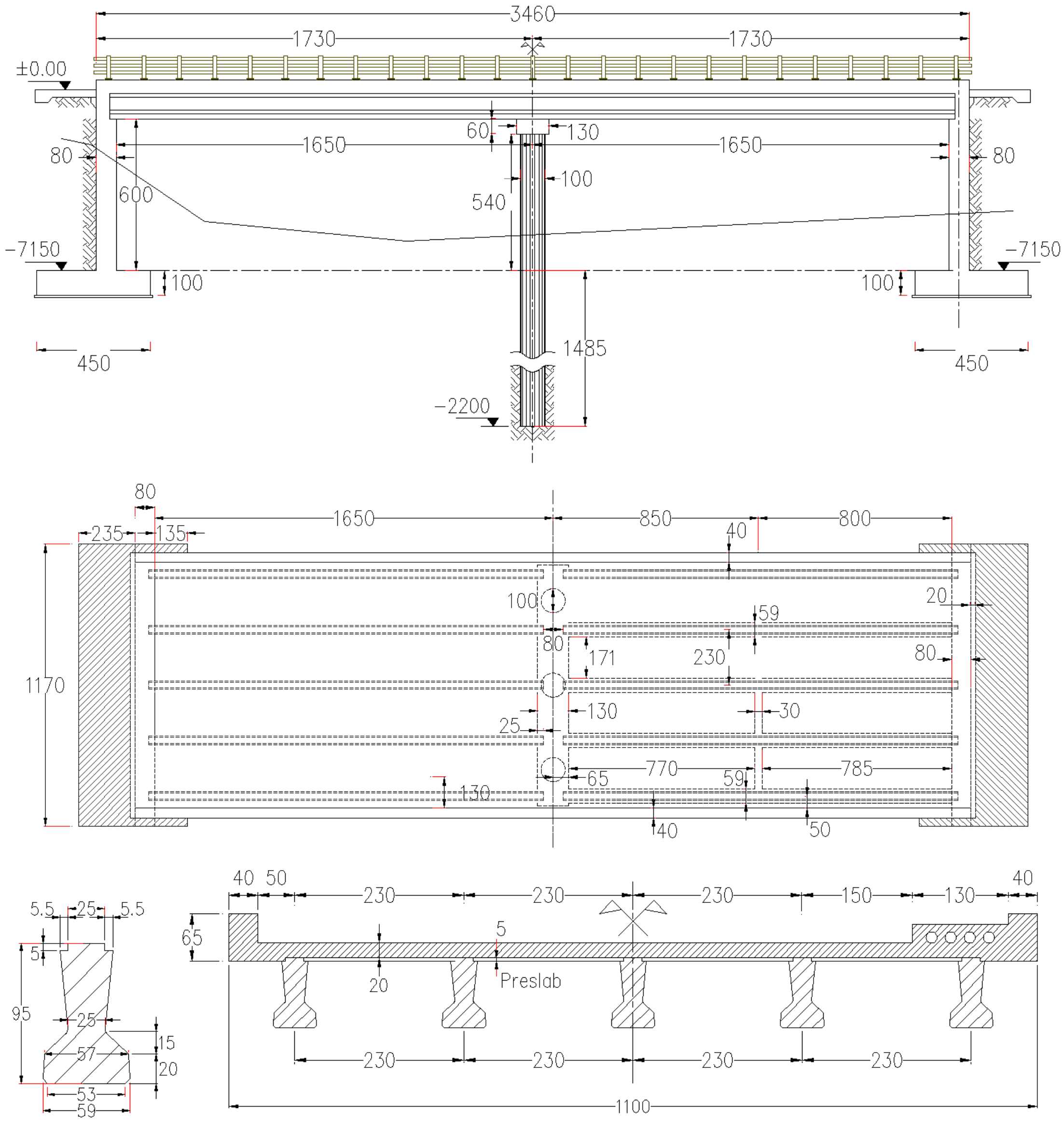


Fig. 2 Geometrical dimensions and cross sections of the bridge (Dimensions are in cm)

In order to examine the level of fixity/integrity of the deck to pier connection, four sensors have been installed in a finer resolution with closer space adjacent to the middle pier (notes by S5, S6, S15 and S16 in Fig.3).

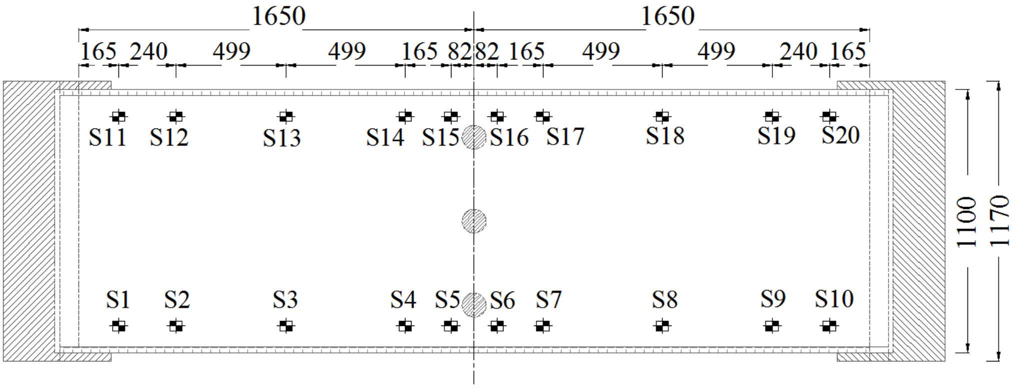


Fig. 3 The measurement grid of the test (dimensions are in cm)

Fig. 4 A photo of the bridge in during the second stage of the modal test

Seven months after the first test, when the bridge was in operational condition, water flow was opened to the river from the upstream dam -after two years- for agricultural purposes. It was a proper opportunity to complete the tests of the bridge for this research. The second stage of the modal test has been done in the condition of the presence of water in the river. The level of water was 2 meter above the riverbed. This test has been carried out with similar conditions and instruments as the first modal test. A photo of the bridge in that time is shown in Fig. 4.

2.2 The tests results

In order to extract the modal parameters, the data obtained from the tests were analyzed. In this study, the data was processed in order to estimate spectral densities with 1024 frequency lines and a frequency line spacing of 0.09766 Hz. This was achieved using an overlapping of 66.67% and applying a Hanning window function. In Fig. 5, plots of the frequency domain decomposition– average of the normalized singular values of spectral density matrices- of the all data sets are shown for both the tests.

The results of the first four natural frequencies extracted from the peak picking technique using the well-known enhanced frequency domain decomposition (EFDD) method are given in Table 1. The corresponding mode shapes for both the tests are shown in Figs. 6 and 7.

It can be seen from Table 1 that the values of the natural frequencies of the bridge corresponding to the second test shows an increase around 2 to 3 percent compared with the first measurement. However, this may not be essentially due to the presence of water flow in the river.

According to the research conducted by Peeters et al. during one year monitoring of Z24 Bridge, an increasing in the temperature of the environment cause to slightly decrease in the natural frequencies of the bridge (Peeters and Roeck 2001). This point has also been examined and approved by Xia *et al*. (2011). It should be noted here that the second test reported here has been carried out in a higher temperature (about 10˚C higher) with respect to the temperature during the first test. Therefore, if the temperature of the environment to be regarded as the main parameter of this difference, the values of the natural frequencies of the second test are to be decreased, while the values have been increased here.

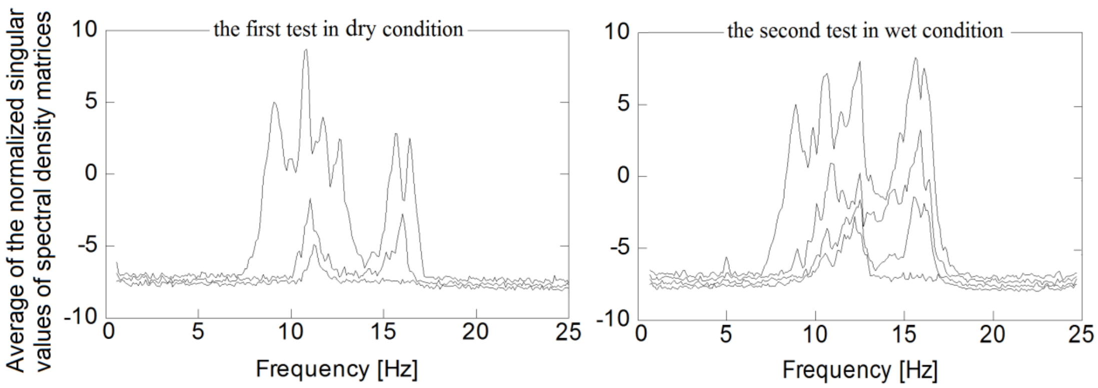


Fig. 5 The frequency domain decomposition plots derived from the tests on the bridge on two different condition of the riverbed

Table 1 Natural frequencies and damping ratios extracted from the tests

Mode #	First test (dry condition of the riverbed)		Second test (wet condition of the riverbed)		Freq. difference (%)	Mode type
	Frequency [Hz]	Damping Ratio [%]	Frequency [Hz]	Damping Ratio [%]		
1	8.88	5.6	9.08	8.5	2.2	1st Bending
2	10.55	1.9	10.84	1.3	2.7	1st Torsion
3	11.43	1.7	11.72	2.6	2.5	2nd Bending
4	12.50	1.8	12.60	2.6	0.8	2nd Torsion

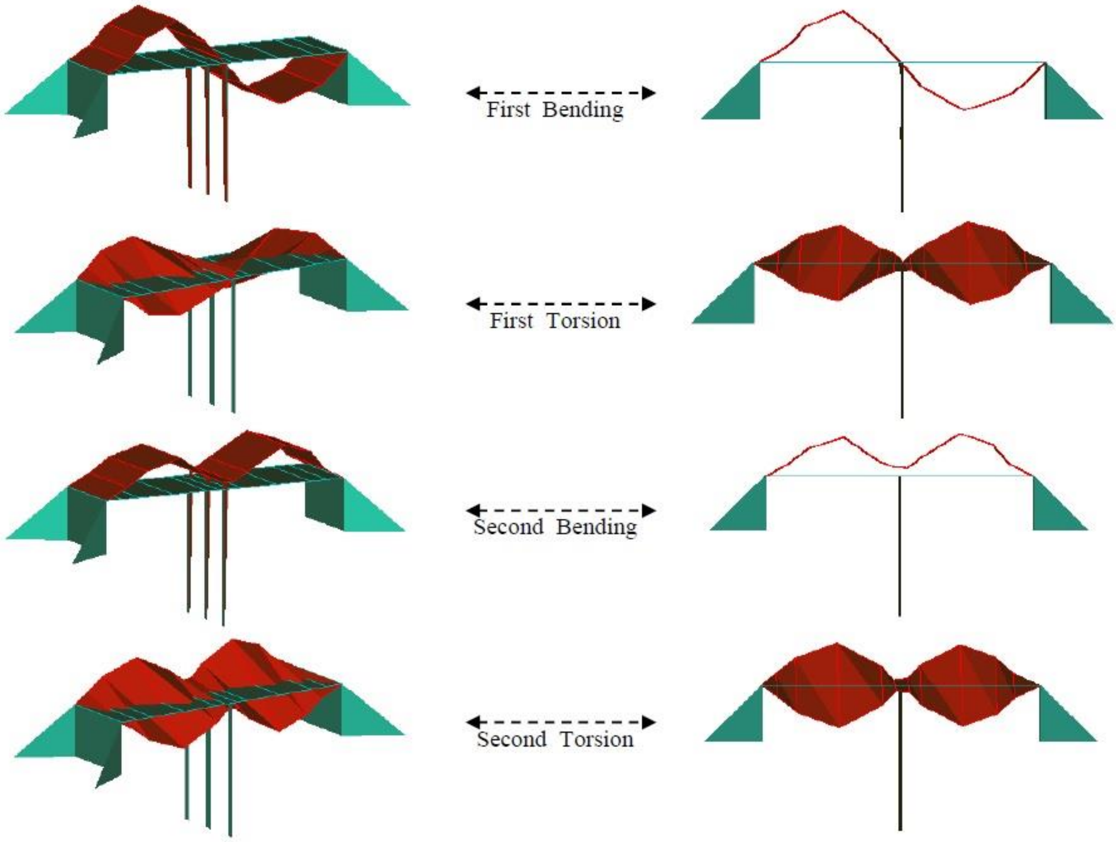


Fig. 6 Mode shapes identified from the first test carried out on the bridge

On the other hand, if the reductions of the values of the natural frequencies associated to the second test due to the higher temperature during the second test to be ignored (assuming similar temporal condition for both the test), the values of the natural frequencies of the second test would be more than that reported in Table 1. This is the real and predicted effect of the riverbed condition or presence of water around the bridge pier and foundation.

Also, the values of the damping ratios of the bending modes of the bridge corresponding to the second test show an increase around 50% compared with the first test. This may be due to the presence of water in the river. For the first and second torsional modes, the values of damping ratios show a decrease around 50% and an increase around 50% respectively.

As the first bending mode of the bridge is dominant in the overall bridge dynamic response, this significant increase in the damping ratio and subsequent increase in the natural frequencies show that the presence of water around the bridge pier and foundation act as a damper for vibration mitigation and cause to slightly increase in the stiffness of the structure, which can be considered as an improvement in the overall dynamic response.

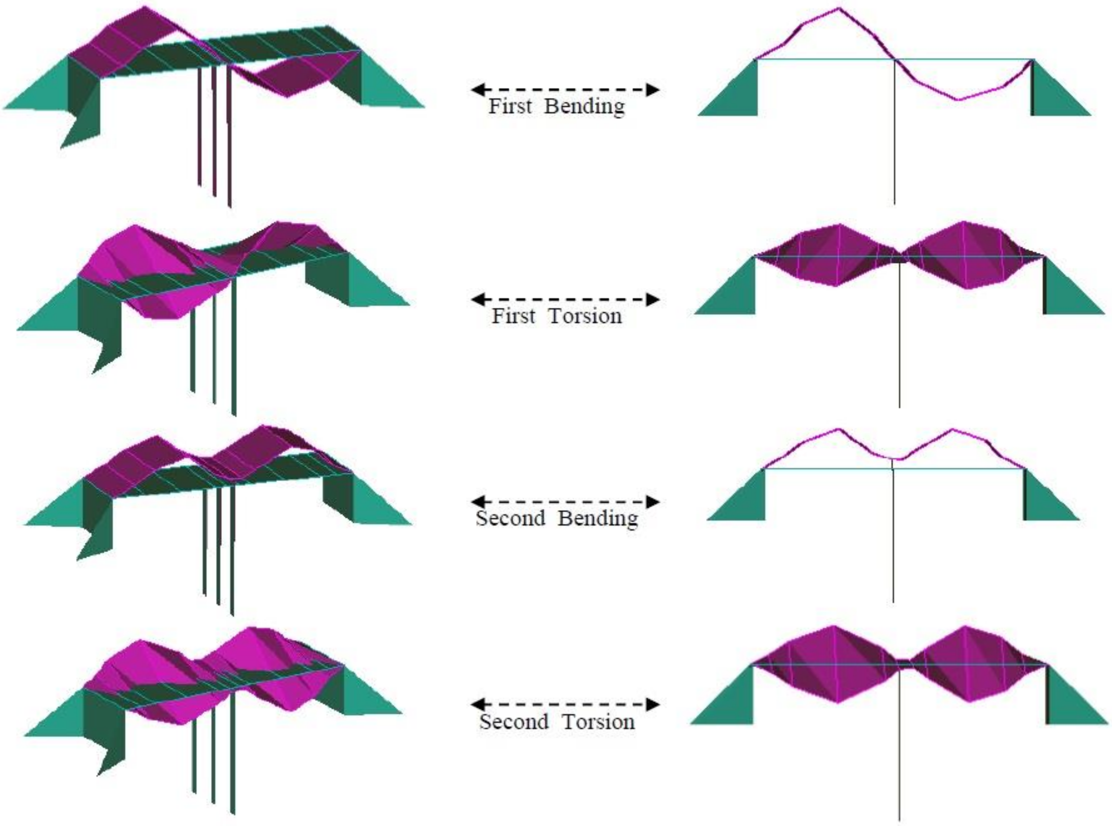


Fig. 7 Mode shapes identified from the second test carried out on the bridge

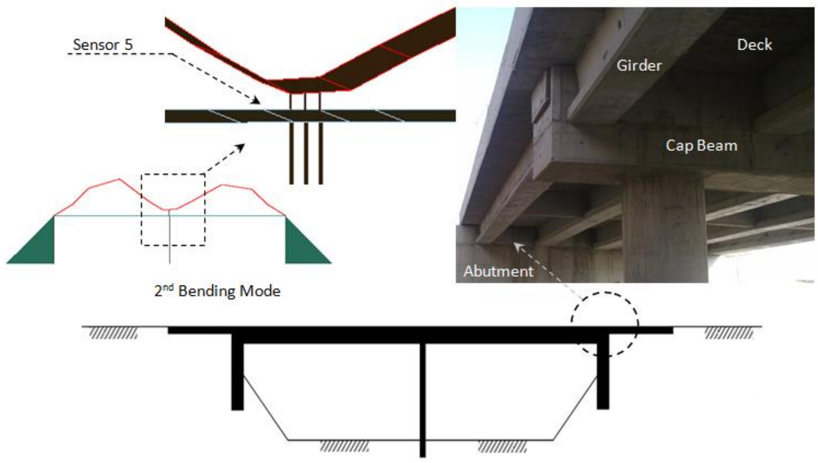


Fig. 8 Rigidity of the superstructure-pier connection

As can be seen from Figs. 6 and 7, the results of the mode shapes for both the first and the second tests are in very good agreements.

The results of the mode shapes extracted from both the tests for the second bending mode show that the analyzed data associated with the sensors number S5, S6, S15 and S16 (see Fig. 3) are in good correlation from displacement and rotation pattern with a fix point similar to a rigid connection. This implies that the superstructure-pier connection act as an integral or rigid frame connection, as shown in Fig. 8.

2.3 Finite Element (FE) modeling

The FE model of the bridge has been created in the SAP2000-CSI Bridge environment according to the design drawings and technical specifications for material properties. Support conditions have been included via restraining all the degrees of freedom for rotation and displacement. The pile-column element has been modeled via frame elements in combination with liner springs as the sub-soil with Elastic Modulus of $2e6\ kN/m^2$. The springs have been included in the FE model for the elements located in the lower level of the riverbed. The riverbed level is 5.33 meter lower than the bottom edge of the cap-beam. The FE model is shown in Fig. 9. The compressive strength of concrete has been used as 30 MPa, which is equivalent to concrete type C35.

The FE analysis results of the natural frequencies and mode shapes are shown in Table 2 and in Fig. 10 respectively. Good agreements and correlation between the values of the natural frequencies and mode shapes have been obtained, as indicated by the MAC parameter (Modal Assurance Criterion) in Table 2. As predicted, the FE model exhibits a more flexible structure than the real bridge, as indicated by the values of the frequency difference in between the results of the FE model and the second test. The FE model is used for parametric analysis regarding the effect of scour depth on the natural frequencies of the superstructure which has been presented in the next section.

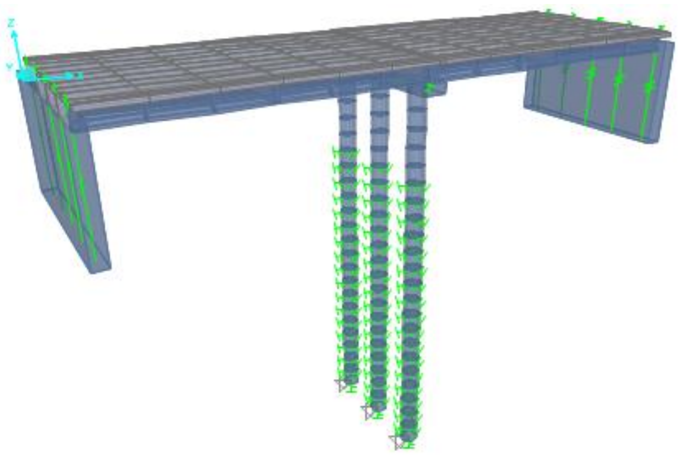
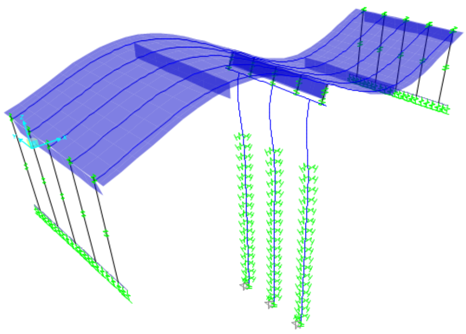


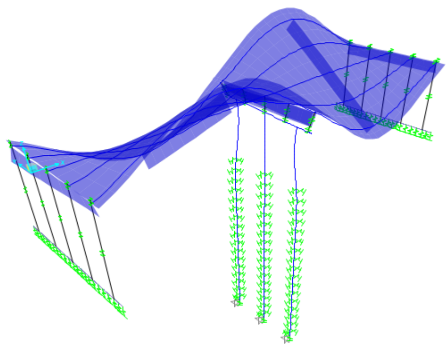
Fig. 9 The FE model of the bridge

Table 2 Natural frequencies obtained from the analysis of the FE model (Hz)

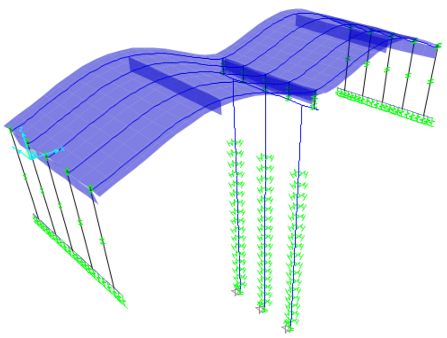
Mode #	Freq. (Hz)	Mode type	MAC	Freq. difference (%) with the second test
1	8.92	1^{st} Bending	0.97	-1.78
2	9.87	1^{st} Torsion	0.96	-8.94
3	10.61	2^{nd} Bending	0.93	-9.47
4	10.90	2^{nd} Torsion	0.94	-13.49



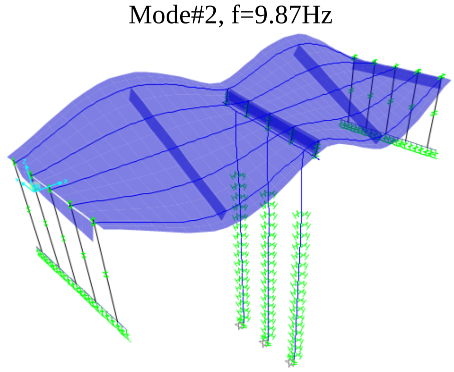
Mode#1, f=8.92Hz



Mode#2, f=9.87Hz



Mode#3, f=10.61Hz



Mode# 4, f=10.90Hz

Fig. 10 Mode shapes obtained from the FE analysis of the bridge

It is to be mentioned that, as the deck is rigidly connected to the piers, the vibration data from experiments are associated from full contribution of the deck-pier complex in three dimensions not from the deck only. This point has not been clearly shown in Figs. 6 and 7, so these figures are only a graphical representation of the deck modal response. In the FE analysis, this point has also been fully considered via rigid connecting the deck to the piers and better represented in Figure 10. Therefore, in the experimental and numerical comparisons, full contribution of the whole structure has been considered.

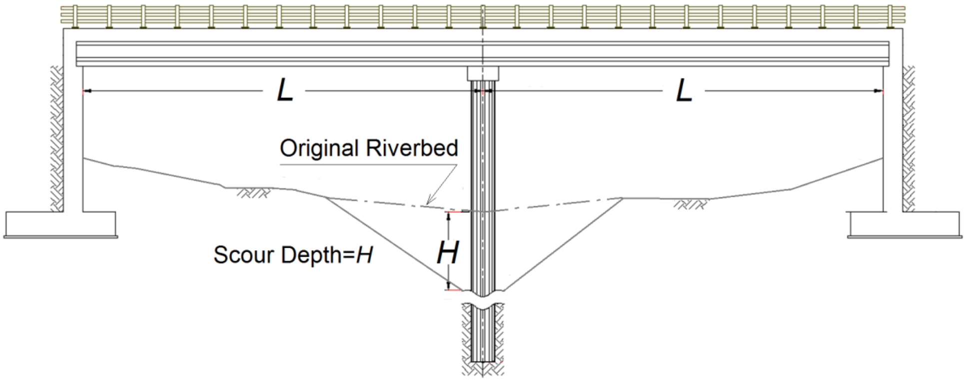
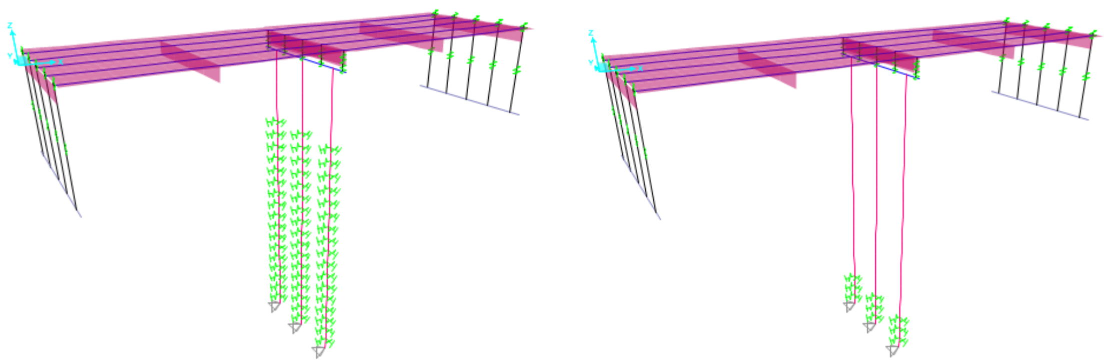


Fig. 11 Definition of parameter H

3. Parametric analyses

In order to investigate the effect of scour depth on the natural frequencies of the bridge, the above mentioned FE model has been employed in a parametric analysis. A non-dimensional parameter has been defined as Relative Scour Depth (RSD), which has been altered from 0 (original bridge with no scour, H=0) to 1.0 (maximum scour, H=14 m) in which the parameter H represents the scour depth in meter as shown in Fig. 11. For each value of the RSD, the associated linear springs of the sub-soil around the piles of the bridge columns to that level from the riverbed are removed from the FE model and the FE models have been analyzed. It was predicted that removing the linear springs from the FE models of the bridge will decrease the stiffness of the structure and its natural frequencies. In Fig. 12, the FE model for two values of the RSD has been shown.



RSD=0 (H=0 or zero scour depth) RSD=1 (or H=14 m)

Fig. 12 Two FE models of the bridge, representing the RSD=0 and 1

Table 3 Different soils and the associated Elastic Modulus (Zhang 2013)

Soil type	Elastic Modulus of the soil (E)
Type #1	$2e6\ kN/m^2$
Type #2	$5e5\ kN/m^2$
Type #3	$4e5\ kN/m^2$
Type #4	$3e5\ kN/m^2$
Type #5	$2e5\ kN/m^2$
Type #6	$1e5\ kN/m^2$

At the same time, different soils have been modeled via entering different values of the Elastic Modulus of the sub-soil in the FE models (different values for the stiffness of the linear springs). The values of the Elastic Modulus of different soils used here are shown in Table 3 (Zhang 2013).

Results of the first four natural frequencies of the FE models of the bridge are shown in Table 4. Variation of the first four natural frequencies of the FE models for different RSD and different soils is shown in Fig. 13. Regarding this fact that no change in the mass of the bridge will be occurred during the scour phenomena, any change in the natural frequency is due to the change in the stiffness of the structure. As noted below the Table 4, for the RSD values greater than 0.5, the mode shape for the third and fourth vibration modes appears in the bridge pier which means that the higher modes effect increases.

The results show that by increasing the scour depth, the natural frequencies of the bridge decreases for all types of the sub-soil in all the vibration modes. This reduction is grater for the values of the RSD higher than 0.5. It is because of this fact that the stiffness of the bridge support with pile-column system is inversely related to the pile length with power of 3. Therefore, when the RSD increases, the free length of the pile increases and the structural stiffness significantly decreases. The percent of reduction in the values of the first four natural frequencies is shown in Figure 14. It is clear that reduction in the value of the natural frequencies is higher for softer soils (lesser values of the Elastic Modulus). Also, the sensitivity of the frequency is more for soil types 5 and 6 with respect to soil types 1 and 2. This is an important result of the present work to be considered by bridge designers and inspectors. Comparison of the natural frequencies of the bridge for different vibration modes and different sub-soil conditions are shown in Figure 15. It is evident that the sensitivity of the frequency with respect to the scour depth can be classified approximately as follows:

- for RSD > 0.7, the fourth vibration mode is more sensitive
- for 0.5< RSD <0.7, the third vibration mode is more sensitive
- for RSD <0.5, the same sensitivity for the first and second and fourth vibration modes and no sensitivity for the third vibration mode.

Using simple second order regression analysis, practical formulas can be obtained that may be used for further researches or practical purposes of similar situations and boundary conditions. The results of the regression analysis are given in Table 5. In these formulas, the parameters f and h represent the first natural frequency (in Hz) and RSD. More data and actual tests are needed for extending such formulas for widespread applications.

Table 4 Results of the first four natural frequencies of the FE models with respect to the RSD for different

Soil type	Relative Scour Depth, RSD							
	0.00	**0.14**	**0.28**	**0.43**	**0.57**	**0.71**	**0.85**	**1.00**
	The first natural frequency (Hz)							
Soil Type #1	8.92	8.78	8.66	8.53	8.35	7.99	7.20	6.21
Soil Type #2	8.85	8.73	8.61	8.47	8.24	7.73	6.82	5.73
Soil Type #3	8.84	8.72	8.60	8.45	8.21	7.67	6.73	5.62
Soil Type #4	8.82	8.70	8.58	8.43	8.16	7.57	6.60	5.45
Soil Type #5	8.78	8.67	8.55	8.39	8.08	7.41	6.38	5.19
Soil Type #6	8.72	8.62	8.49	8.28	7.85	6.98	5.88	4.74
	The second natural frequency (Hz)							
Soil Type #1	9.87	9.78	9.70	9.60	9.42	8.85	7.58	6.38
Soil Type #2	9.82	9.74	9.66	9.54	9.27	8.37	7.08	5.86
Soil Type #3	9.81	9.74	9.65	9.53	9.22	8.26	6.98	5.73
Soil Type #4	9.80	9.72	9.64	9.51	9.15	8.10	6.83	5.55
Soil Type #5	9.78	9.71	9.62	9.46	9.00	7.85	6.57	5.28
Soil Type #6	9.74	9.66	9.56	9.32	8.55	7.27	6.02	4.81
	The third natural frequency (Hz)							
Soil Type #1	10.61	10.61	10.61	10.61	10.61*	9.24*	7.75*	6.52*
Soil Type #2	10.61	10.61	10.61	10.61*	10.61*	8.61*	7.24*	5.99*
Soil Type #3	10.61	10.61	10.61	10.62	10.61*	8.49*	7.13*	5.86*
Soil Type #4	10.61	10.61	10.61	10.61	10.60*	8.31*	6.97*	5.68*
Soil Type #5	10.61	10.61	10.61	10.61	10.34*	8.03*	6.71*	5.40*
Soil Type #6	10.61	10.61	10.60	10.61	8.82*	7.43*	6.15*	4.93*
	The fourth natural frequency (Hz)							
Soil Type #1	10.90	10.85	10.79	10.70	10.40*	10.05*	8.13*	6.73*
Soil Type #2	10.87	10.83	10.76	10.64*	10.04*	9.18*	7.53*	6.15*
Soil Type #3	10.87	10.82	10.75	10.58	9.93*	9.01*	7.40*	6.01*
Soil Type #4	10.86	10.81	10.74	10.55	9.77*	8.79*	7.23*	5.81*
Soil Type #5	10.85	10.80	10.72	10.47	9.48*	8.44*	6.93*	5.52*
Soil Type #6	10.82	10.76	10.65	10.13	9.40*	7.72*	6.31*	5.02*

*mode shape appears in the bridge pier

Table 5 Results of the regression analysis for the first natural frequency as function of RSD

Elastic Modulus of Soil (Es)	Formula	R^2 factor
$2e6\ kN/m^2$	$f=-3.528h^2+1.204h+8.77$	0.997
$5e5\ kN/m^2$	$f=-4.312h^2+1.498h+8.70$	0.985
$4e5\ kN/m^2$	$f=-4.508h^2+1.54h+8.69$	0.986
$3e5\ kN/m^2$	$f=-4.704h^2+1.61h+8.67$	0.988
$2e5\ kN/m^2$	$f=-5.096h^2+1.708h+8.63$	0.991
$1e5\ kN/m^2$	$f=-5.292h^2+1.47h+8.61$	0.996

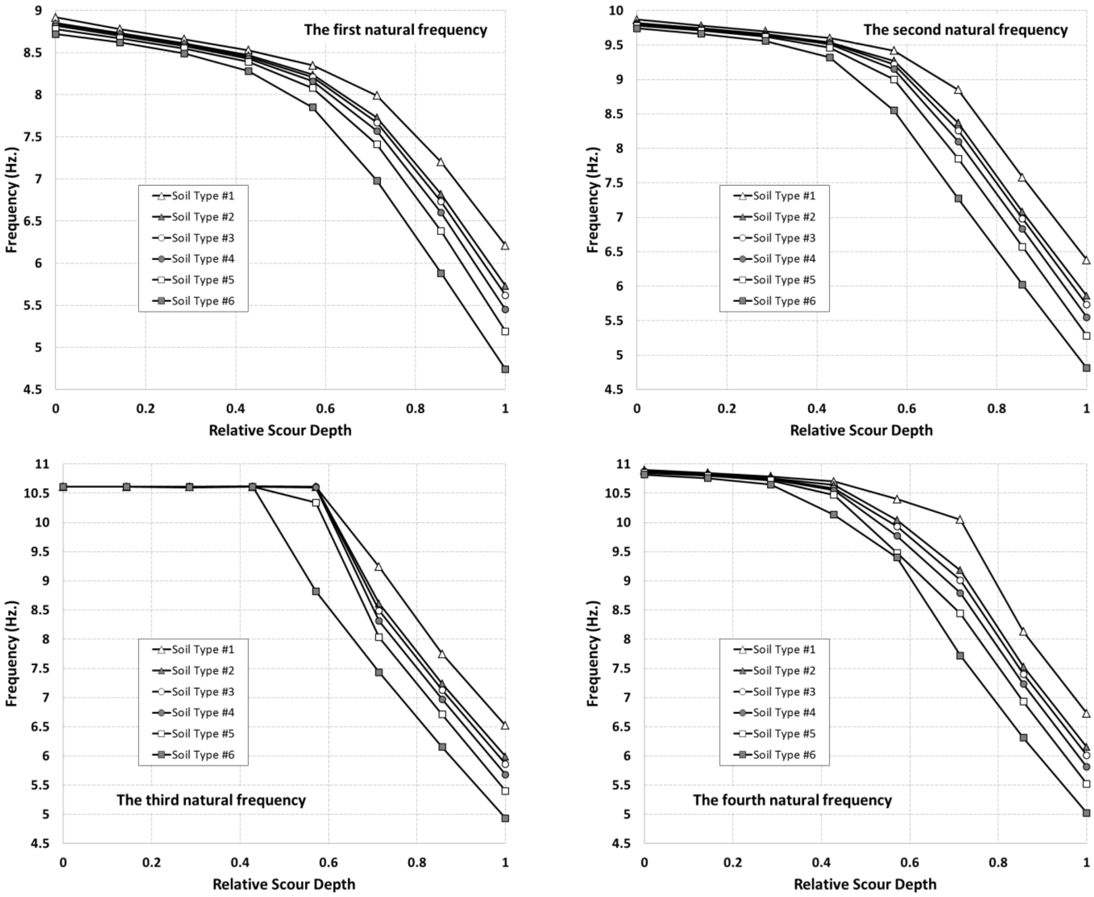


Fig. 13 Variation of the first four natural frequencies of the bridge with respect to the RSD for different sub-soils

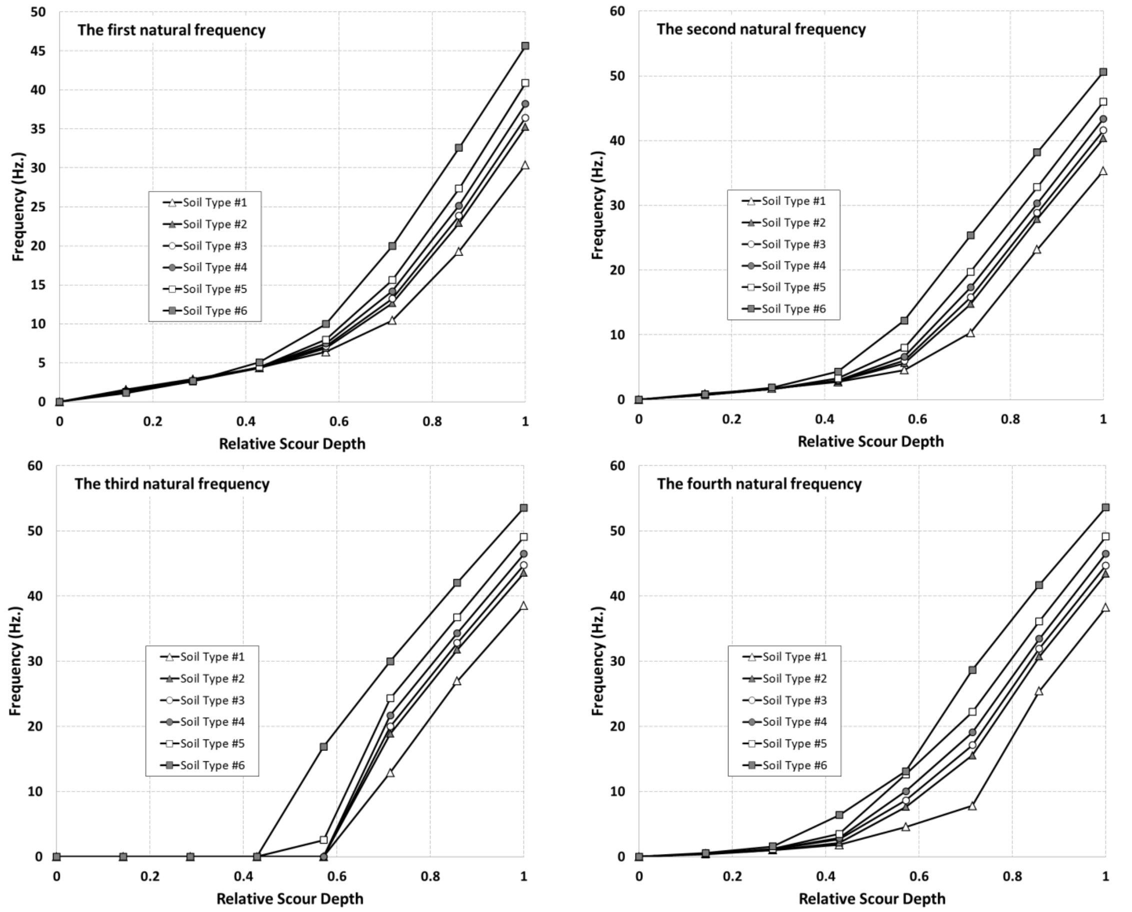


Fig. 14 Variation of the percent of reduction of the first four natural frequencies of the bridge with respect to the RSD for different sub-soils

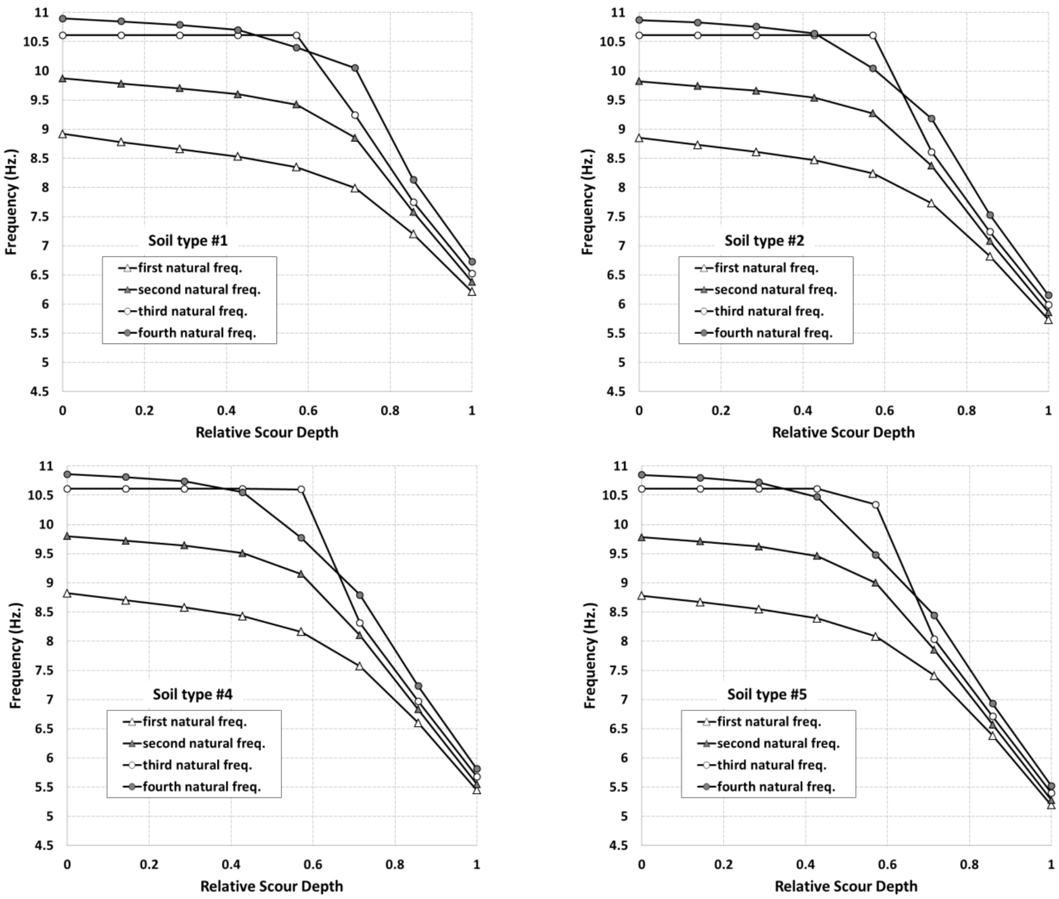


Fig. 15 Comparison of the natural frequencies of the bridge for different vibration modes and different sub-soils

4. Conclusions

According to the results of this research it can be concluded that presence of water around the pier of this integral abutment bridge may act as a damper which lead to significant increase in the damping ratios and slightly increase in the structural stiffness and its natural frequencies. The later can slightly improve the dynamic performance of the structure. Regarding the effect of the scour depth, the results show that the values of the natural frequencies of the bridge decrease by increasing in the values of the relative scour depth. The rate of this reduction is found to be 0 to 13 percent for relative scour depths ranging from 0 to 0.6 and to be 13 to 50 percent for relative scour depths higher than 0.6. Finally, the results show that the rate of reduction of the values of the natural frequency due to the occurrence of the scour is higher for softer soils, those have lower values of the Elastic Modulus.

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