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DYNAMIC CHARACTERISTICS OF BRIDGE-FOUNDATION-SOIL SYSTEMS BASED ON LABORATORY AND ON-SITE MEASUREMENTS

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ABSTRACT: The natural frequencies of the Metsovo bridge during construction are identified both in actual scale and in 1:100 scale. Finite element models of increasing modeling complexity are developed in order to investigate their efficiency in representing the measured dynamic stiffness of the bridge-foundation-soil system. The results highlight the importance of accurately simulating boundary conditions in Structural Health Monitoring applications.

KEY WORDS: Bridges; caissons; finite elements; soil-structure interaction.

1 INTRODUCTION

The dynamic characteristics of structures can be either identified through System Identification (SI) methods or predicted by modal analysis of numerical finite element (FE) models. System Identification methods can identify the modal properties of structures by measuring their response to a known excitation (input-output methods, [1], [2]) or to an unknown excitation (output-only methods, [3], [4]). The modeling assumptions of the FE models can be evaluated by comparing the identified with the predicted modal characteristics. A wide variety of studies ([5], [6] and [7]) present the influence of soil stiffness to the SI results and the importance of taking into account soil compliance in FE models, in order to minimize the discrepancies between identified and numerically predicted dynamic characteristics.

One option to account for soil compliance is by numerically modeling the entire structure-foundation-soil system as a whole [8]. Due to the fact that this method is quite expensive from a computational standpoint and is not easily implemented in engineering practice, alternative methods have also been developed. In these methods the structure-foundation-soil interaction is decoupled to kinematic and inertial component. As far as the shallow embedded foundations are concerned, it is common to replace the foundation-soil system with six degrees-of-freedom (DOF) springs, the stiffness of which is calculated according to Elsabee et al. [9]. Alternatively, the subsoil may be replaced by 6-DOF springs concentrated at the base of the foundation (defined according to Kausel [10]) as well as additional springs attached on the foundation [11]. Experimental and numerical evaluation of the efficiency of the aforementioned methods in representing the dynamic stiffness of various foundation-soil systems is presented by Gerolymos et al. [11].

The scope of this paper is to experimentally verify the influence of soil compliance on the predictions of System Identification and to investigate the efficiency of existing numerical methods in simulating the soil stiffness. Measurements on the prototype structure during construction are compared to the dynamic characteristics obtained by laboratory testing of a scaled structure while the influence of different soil conditions is also investigated both experimentally and numerically. The results show good agreement between the identified and the numerically predicted natural frequencies, highlight specific discprepancies and quantify the effect of soil compliance on the bridge-foundation-soil dynamic characteristics.

2 PROTOTYPE STRUCTURE

The Metsovo ravine bridge was constructed in 2008 in Greece along the Egnatia Highway and consists of two structurally independent branches (one for each carriageway). The bridge was constructed by the balanced cantilever construction method, which made feasible the modal identification of structurally independent bridge components during construction. The modal characteristics of the M3 (cantilever) pier (*Figure 1*, *left*) were identified prior to the construction of the key connecting segments to the M2 pier, the latter also temporary acting as a balanced cantilever [13]. The total length of the deck supported on the M3 cantilever was, at the time that the measurements were obtained, 215m while the height of the pier was 32m. The latter is founded with a large caisson embedded in thick interchanges of sandstone and limestone, which roughly correspond to soil class A according to Eurococe 8 [12]. The modal identification of the M3 cantilever was based on ambient vibration measurements triggered by wind and induced operational loads. Detailed information regarding the measurements and the applied identification methodology can be found in [13].

Figure 1. Metsovo Bridge segments under during the construction stage (left) and its equivalent scaled structure tested at the laboratory (right).

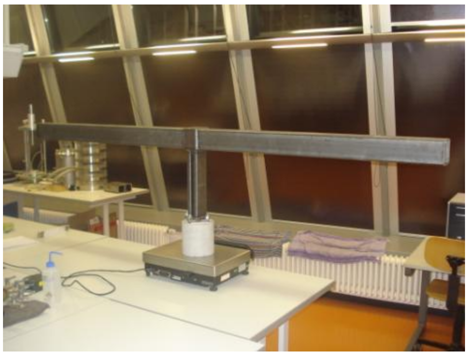


Figure 2. Scaled structure on concrete caisson before placement within the stabilized soil.

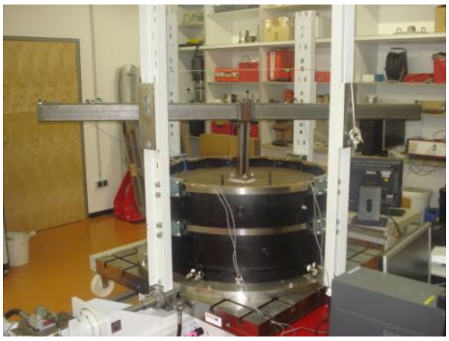


Figure 3. Scaled structure on stabilized soil.

3 SCALED STRUCTURE WITH ALTERNATIVE BOUNDARY CONDITIONS

A scaled model structure of the prototype M3 pier cantilever of Metsovo Bridge was constructed in the laboratory of Soil Mechanics at the Bauhaus University Weimar. Apart from the stiff foundation soil corresponding to the actual conditions of the prototype structure, alternative boundary conditions were also examined in the form of gradually stabilized soil to investigate the influence of soil compliance on the prediction of modal characteristics.

3.1 Scaled structure fixed

The construction of a scaled structure dictates the determination of the scaling laws relating the prototype geometry to that of the scaled structure. The scaling laws can be determined either by dimensional analysis or the analysis of the system's characteristic equation. Based on dimensional analysis and by neglecting the gravity distortion effects that arise during scaling, the scaling factor that relates the natural frequencies of a scaled structure with its prototype is given in Eq. (1) [14]:

$$\lambda_f = \frac{1}{\lambda_l} \cdot \sqrt{\frac{\lambda_E}{\lambda_\rho}} \tag{1}$$

where: λ_f is the prototype to the model frequency ratio,
λ_l is the prototype to the model dimension ratio,
λ_E is prototype to the model young modulus of Elasticity ratio,
λ_ρ is prototype to the model density ratio.

Herein, the scale set to 1:100, to accommodate the fact that the deck length of the prototype structure is 215m (*Figure 1)*. It is noted that as the exact section of the concrete deck could not be reproduced at a 1:100 scale (i.e., the resulting web and flanges would be as thin as 22 mm and 3 mm) an equivalent steel structure with the same dynamic characteristics was formed in the laboratory based on parametric modal analysis. Several standard steel sections were considered until matching with the modal characteristics of the concrete scaled structure was achieved. The equivalent, steel balanced cantilever was finally formed by the following commercially available sections:

- a 90X90X3 HSS steel hollow section of 215cm length corresponding to an 1:100 replication of the prototype deck,
- a 100X100X5 HSS steel hollow section of 6,15cm length corresponding to the prototype central deck-segment, and
- a 80X20X3 HSS steel hollow section of 32cm length corresponding to 1:100 replication of the prototype M3 pier.

3.2 Scaled structure on stabilized soil

Next, the scaled structure was fixed on a circular concrete foundation (15cm diameter and height) with four screws as shown in *Figure 2*. The structure was then placed within a 95cm diameter laboratory box that was filled with stabilized soil (*Figure 3*). The stabilized soil consisted of clay (CL), with 24% water and 4% lime. The latter was added in order to increase the stiffness of the soil and its percentage was determined according to DIN EN 459-1 [15]. A standard Proctor compaction test was also conducted in order to define the optimal water content of the soil mix and to achieve its maximum dry density.

The stabilized soil was placed into the laboratory box in seven layers. Each layer had a depth of 5cm and was compacted to reach its maximum density. The total height of the stabilized soil in the box was 30cm and the dry density was determined as ρ_s=1.86t/m^3. Sensors were placed inside the box in order to measure the shear wave velocity of the stabilized soil.

4 FINITE ELEMENT MODELS

4.1 Fixed conditions

A refined finite element (FE) model using three-dimensional solid elements was developed to simulate the fixed scaled structure as shown in *Figure1 (right)*. A sensitivity analysis was primarily conducted to investigate the model error due to FE discretization. The resulted FE model consisted of approximately 19,000 triangular elements corresponding to 88620 degrees of freedom. The measured mass of the physical model was 20.46kg with a density of ρ=7.46t/m^3. The modulus of elasticity of the stainless steel was taken equal to 210GPa.

4.2 Soil compliant conditions

Several FE models were developed for the scaled structure fixed on a concrete foundation (*Figure 2*) and then embedded within the stabilized soil (*Figure 3*).

4.2.1 Holistic method

A three-dimensional finite element model of approximately 200,000 degrees of freedom was further developed for the entire pier-foundation-subsoil system. Stainless steel (E=210GPa, v=0.3) was once more assigned to the superstructure, whereas C30/37 concrete properties (E=37GPa, v=0.3) were assigned to the caisson. The mass of the foundation was measured 7.56kg corresponding to a density ρ=2.71t/m^3. The shear modulus of the stabilized soil was taken equal to G=186MPa based on the shear wave velocity V_S=316m/s and density ρ_s=1.86t/m^3 values that were measured in the laboratory.

4.2.2 Inertial and kinematic interaction

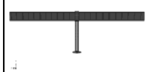
4.2.2.1 Large diameter caisson model

Soil was modeled through 6-DOF springs at the base of the foundation and by 6-DOF springs at the middle of the foundation height. The stiffness of the former springs was obtained from the theory of rigid circular foundations on a stratum over rigid base suggested by Kausel [10] while the stiffness of the latter springs was calculated by the solution of Gerolymos et al [11] for cylindrically shaped large diameter caisson foundations. In these formulas the soil shear modulus G was again estimated based on the measured V_S of the stabilized soil.

4.2.2.2 Shallow embedded cylindrical foundation model

Both the foundation and the soil were replaced by 6-DOF Winkler type springs. Their values were obtained from the theory of rigid embedded cylindrical foundations welded into a homogenous soil stratum over bedrock, proporsed by Elsabee et al. [9]. Again the G shear modulus was also estimated based on the measured V_S of the stabilized soil.

Table 2. Identified and numerically predicted natural frequencies for the case that the scaled structure was fixed at its base.

Modes	M3 cantilever **Prototype on Rock [13]**	**Ideal 1:100 scaled structure**	Equivalent scaled (steel) structure **Fixed**	FE model of the equivalent scaled (steel) structure **Fixed**
		*Theoretical (not constructed)*		
	(Hz)	(Hz)	(Hz)	(Hz)
Rotational	0.159	15.90	15.96	16.01
1st Longitudinal	0.305	30.50	23.67	23.13
Transverse	0.623	62.30	65.56	68.23
2nd Longitudinal	0.686	68.60	67.68	69.71
Bending (deck)	0.908	90.80	88.65	89.45
Average Δf (%)			**6.34%**	**2.12%**

5 RESULTS

5.1 Prototype structure vs. equivalent scaled structure

The first five identified natural frequencies of the M3 cantilever prototype structure range between 0.159-0.908Hz and are presented in Table 2. The corresponding natural frequencies that are theoretically anticipated for an 1:100 scaled structure, ideally comprising of the same material, are also presented in Table 2 and vary between 15.90Hz and 90.80Hz. These expected natural frequencies are used to validate the equivalence of the constructed scaled (steel) structure with the prototype.

The equivalent scaled (steel) structure was subjected to hammer impulses in order to simulate a broad band excitation, similar to ambient excitations applied to the actual M3 cantilever. The natural frequencies were identified by the stochastic subspace identification method [4] with the use of MACEC, which is a Matlab toolbox for operational modal identification. The first five identified natural frequencies given in Table 2 range between 15.96-88.65Hz. It has been observed that the natural frequencies of the equivalent scaled structure present a 6.34% average deviation compared to those expected from the prototype's ideal 1:100 scaled structure, indicating good agreement between the equivalent (steel) and the prototype (concrete) bridge pier.

Table 3. Identified and numerically predicted natural frequencies for the case that the foundation of the scaled structure was embedded in stabilized soil.

Modes	Scaled structure on **stabilized soil**	FE model on **stabilized soil** ***Holistic method*** *G=186MPa*	FE model on **stabilized soil** ***6+6 DOFs springs*** *Kausel [10] Gerolymos [11] G=186MPa*	FE model on **stabilized soil** **6 DOFs** ***springs*** *Elsabee [9] G=186MPa*
				
	(Hz)	(Hz)	(Hz)	(Hz)
Rotational	14.88	15.65	15.64	15.82
1st Longitudinal	19.15	21.79	21.74	21.98
Transverse	46.52	57.65	57.01	60.6
2nd Longitudinal	56.87	63.89	63.43	66.59
Bending (deck)	85.25	88.77	88.72	88.76
Average Δf (%)		**11.87%**	**11.36%**	**14.51%**

5.2 Identified and numerically predicted natural frequencies

5.2.1 Fixed boundary conditions

Next, the efficiency of the numerical model to capture the dynamic characteristics of the fixed scaled (steel) structure was carefully validated. It is indeed verified that the first five natural frequencies predicted by the fixed FE model and range between 16.01-89.45Hz are in very good agreement with those of the tested equivalent structure showing only a 2.12% average error as are summarized in Table 2.

5.2.2 Stabilized soil as foundation soil

A hammer impulse excitation was also applied to identify the natural frequencies of the scaled structure when the latter was placed within the stabilized soil. The first five identified natural frequencies are presented in Table 3, and range between 14.88-85.25Hz. The numerical predictions of the three alternative methods to account for soil compliance are also presented in the same Table. It is observed that the average deviation between the identified and the numerical predicted frequencies range is of the order of 11-14%. This deviation is not significant but also not negligible as well given the controlled nature of the laboratory testing. Given that the experimentally and numerically predicted natural frequencies of the fixed system were almost identical, it is evident that this difference is clearly attributed to the method used to represent soil stiffness using equivalent springs, as well as to the determination of the actual soil stiffness at the laboratory. It is interesting to notice that even though the hammer excitations were of low intensity and the induced soil shear strain subsequently small, the value of soil stiffness that was introduced in the numerical model was overestimated.

6 CONCLUSIONS

This paper presents an effort to comparatively assess the efficiency of numerical models to capture the effect of soil compliance on the predicted dynamic characteristics of bridge-foundation-soil systems. The study focuses on the case of the Metsovo bridge durin the construction stage where measurements were made available and compared to the results of equivalent scaled systems tested in the laboratory. Due to the difficulties in constructing an actual concrete deck at a scale 1:100, an equivalent steel scaled structure was constructed in the laboratory presenting minimum deviation (as low as 6%) in terms of dynamic characteristics. The respective finite element model also successfully predicted the natural frequencies of the fixed scaled structure presenting a 2.12% average error. When the scaled structure was embedded in stabilized soil, the natural frequencies decreased as anticipated. This decrease was observed both experimentally and numerically for all considered modes. Three methods were adopted to simulate the soil compliance of the stabilzed soil, namely: (a) a holistic method with 3D solid finite elements, (b) a 6+6 DOF springs method suggested by Kausel [10] and Gerolymos et al [11] and (c) a 6-DOF spring method introduced by Elsabee [9]. The average deviation between the identified and the numerically predicted natural frequencies range at all three methods between 11.3-14.5%, indicating that the stabilized soil's measured shear modulus was probably overestimated. Despite this, the influence of soil compliance was demonstrated by all numerical and experimental data thus highlighting the necessity of carefully considering soil compliance in the framework of structural health monitoring.

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