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Optimal sensor placement techniques for modal identification of historical masonry structures

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Abstract

Since destructive tests are not allowed for historical structures, numerical model updating using accelerometers has gained a lot of attraction in the last decade. Furthermore, another application of structural health monitoring is damage detection for near-real-time monitoring of cultural heritage assets of infrastructures such as masonry bridges. However, high cost is the main problem that discourages the use of large-scale structural health monitoring systems, and a modal pretest analysis is required to plan and optimize the modal tests procedure. For this purpose, various optimal sensor placement (OSP) techniques have been developed to derive the operational modal analysis results with a minimum number of sensors, leading to a lower cost. In this study, various OSP techniques have been applied to optimize sensor placement in two selected case studies. The first case study is a two-span masonry arch bridge in Rhodes, Greece and the second is a stone masonry tower located in Tønsberg, Norway. Baseline finite element models were developed before performing the ambient vibration tests and model updating process. The optimum sensor locations were detected using various techniques, and a comparative study was conducted on the results. Furthermore, the effect of considering soil-structure interaction on the OSP results was investigated.

Keywords: Optimal sensor placement; Structural health monitoring; Historical masonry structures.

1. Introduction

Conservation of cultural heritage assets is crucial for every nation not only due to their spiritual point of view but also for their importance as tourist attractions that influence the economic growth of countries, as highlighted by

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Shabani et al. (2020). However, irreparable loss of cultural heritage assets because of man-made and natural hazards has been warned by the international organizations involved in the preservation of cultural heritage assets, based on Valagussa et al. (2021). Fig. 1 illustrates the UNESCO cultural heritage sites map of the European countries and the seismic, landslide and active volcanoes hazard maps. The concentration of cultural heritage assets in high seismicity zones with high susceptibility to landslide and active volcanoes risks can be concluded, especially in southern European countries.

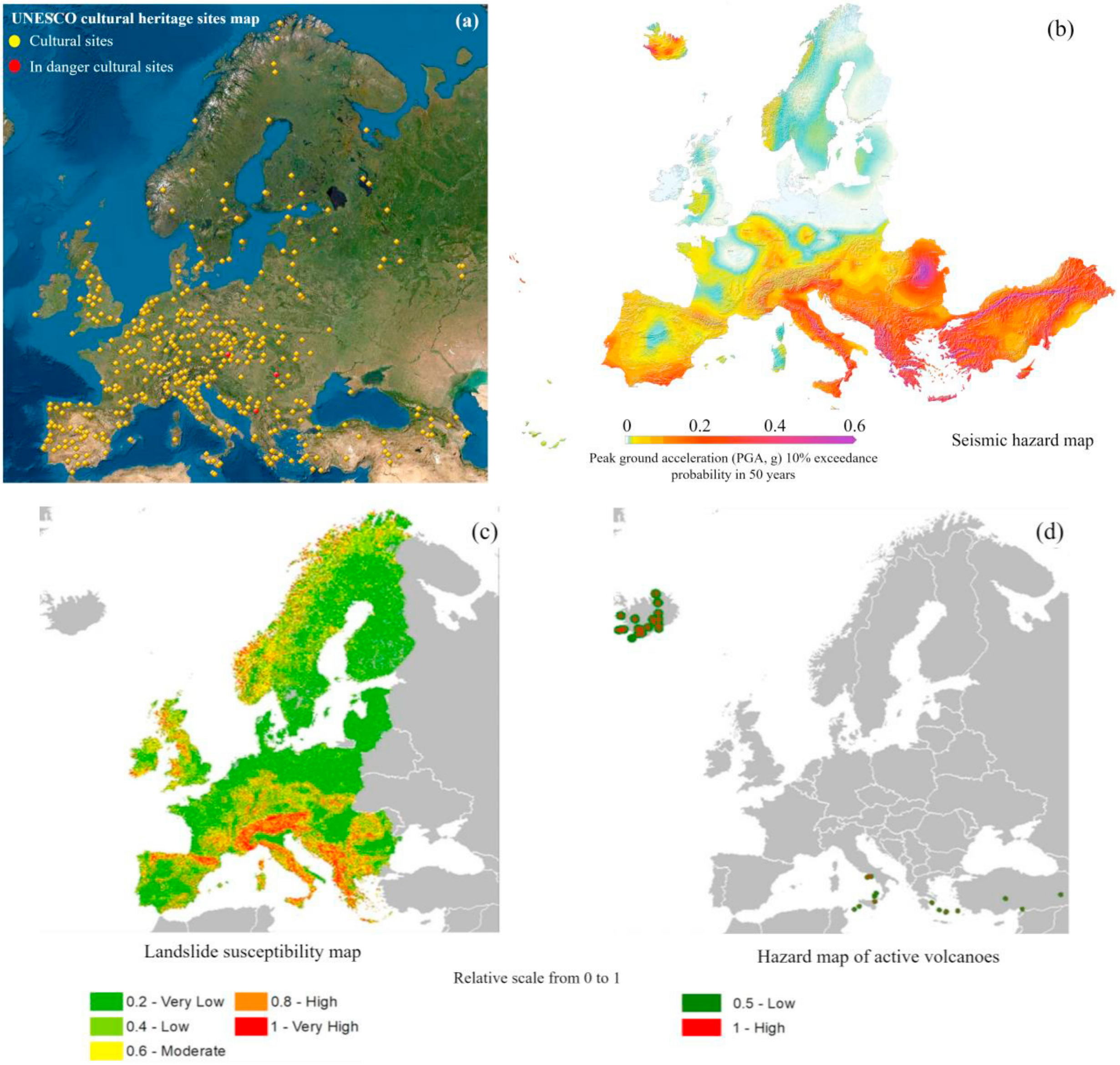

Fig. 1. (a) The UNESCO cultural heritage sites map (adapted from https://whc.unesco.org/), (b) seismic hazard map developed by Danciu et al. (2021), (c) landslide susceptibility map presented by Günther, Van Den Eeckhaut, et al. (2014) and (d) hazard map of volcanoes presented by Günther, Hervás, et al. (2014).

Various methodologies have been developed and applied for the vulnerability assessment and conservation of architectural heritages, as highlighted by Shabani, Kioumarsi, et al. (2021), and Shabani, Alinejad, et al. (2021). Destructive tests are not allowed to be employed for investigating the mechanical properties of historic structures.

Therefore, structural health monitoring and damage detection using accelerometer sensors can be one of the most reliable methods for either predicting the vulnerability or near-real-time assessment of historical structures as presented by Angjeliu et al. (2020). Furthermore, material properties can be defined by calibrating the FEMs based on the operational modal analysis (OMA) results which are based on ambient vibration testing (AVT) using accelerometers as elaborated by Pallarés et al. (2021). However, the cost of sensors is one of the main limitations of these methods. To tackle this limitation, various optimal sensor placement (OSP) methods have been proposed for detecting the best location of the limited number of sensors before performing the tests to derive the dynamic characteristics of structures such as mode shapes as presented in Tan & Zhang (2020). In recent decades, there have been many contributions in this area. Fig. 2 shows the evolution of the number of journal papers related to the OSP topic, structural health monitoring, and damage detection topics using the Scopus database. However, the application of the OSP methods to historical structures with complex architecture should be investigated.

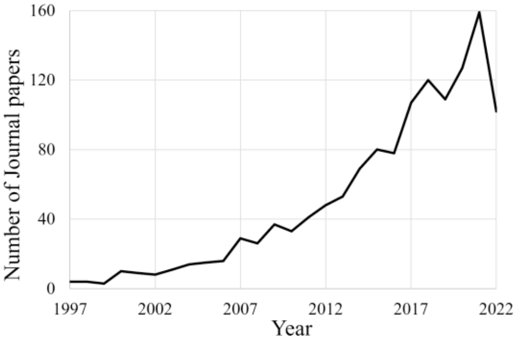

Fig. 2. The number of journal papers related to the OSP and structural health monitoring using the Scopus database.

In this paper, a stone masonry tower and a stone masonry arch bridge were chosen to be studied as two representations of historical structures. The application of five OSP methods to the selected case studies has been investigated. In the first step, finite element models of the case studies were developed, and the initial material properties were assigned. Afterward, the OSP analyses were carried out, and the results of different methods were compared. In addition, the effect of soil-structure interaction was taken into account for the tower, and the results of the OSP methods were compared to the results of the models with rigid boundary conditions.

2. OSP methods and acceptance criterion

OSP methods can be categorized into two main groups as presented in Fig. 3, which are sensor placement metrices and sensor elimination methods. Each method in Fig. 3 was chosen to be applied to the case studies and presented in this section.

Sensor placement methods are based on sensor placement metrices to detect the candidate sensors. Normalized modal displacement (NMD) is based on the observability of target modes using the information on weighted modal displacement. Although various types of modal displacements can be utilized, the weighted modal displacement was chosen as prescribed by FEMtools (2021). In the Normalized kinetic (NKE) method, the distribution of the kinetic energy for a particular mode is considered the metric for detecting the locations with large modal participation.

The main aim of the sensor elimination methods is to reduce the sensors from the first candidates and investigate the effect of elimination criteria. The Effective independence method (EIM) uses linear independence of mode shapes as an elimination criterion by avoiding the singularity of the Fisher information matrix based on Demirlioglu et al. (2023). The modal assurance criterion (MAC) is commonly utilized to compare the mode shape by calculating the squared cosine of the angle between two mode shapes. The main goal of the sensor elimination using MAC (SEMAC) method sensor elimination process is to minimize the off-diagonal terms of the MAC matrix. The idea of the iterative Guyan reduction (IGR) method is to eliminate the degree of freedom with small mass-to-stiffness ratios from the model by computing the reduced mass and stiffness matrices based on Ostachowicz et al. (2019).

Although sensor placement metrices methods are computationally efficient, the linear independence is not investigated and can be checked based on the MAC matrix. Unlike sensor placement metrices methods, linear independence, which is important for distinguishing each mode from others, is taken into account in the sensor elimination methods. Various acceptance criteria have been suggested to investigate the quality of the OSP methods as described by Tan & Zhang (2020). MAC matrix is one of the acceptance criteria to investigate the observability of the modes and their independence. MAC matrix criterion is commonly used for mechanical and structural applications, which is utilized as the criterion in this study. There is no standard for this criterion, but the off-diagonal terms of the MAC matrix should be less than 40% suggested by FEMtools (2021).

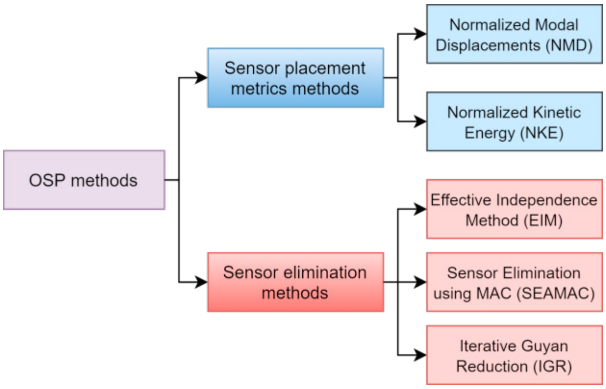

Fig. 3. Different OSP methods and their classification.

3. Case studies

Historical structures are known to be complex in terms of architecture, as mentioned by Miccoli et al. (2021). Masonry arch bridges and masonry towers are two conventional types of historical structures together with mosques, churches, monasteries, and aqueducts. In this section, the OSP methods were applied to a masonry arch bridge and a masonry tower. For the OSP analysis, seven uniaxial accelerometers were taken into account for both case studies.

3.1. Stone Masonry Bridge (Roman Bridge)

The Roman bridge (see Fig. 4.) is on Rhodes Island in Greece and is dated back to the Roman period. The structure is under service load, but extensive damages can be seen under the arches. Although temporary timber scaffolds were installed, a strengthening strategy should be decided to avoid future damages due to the car and truck loads and the possible seismic loads. The Roman bridge is a stone masonry bridge with two arches. The radius of the arches and the widths are 3.2 m and 8.4 m, respectively. 3D models of the structure were provided using the areal images (drones) and ground images (cameras) together with 3D laser scanners. In addition, 3D finite element models were developed as elaborated by Shabani, Skamantzari, et al. (2022). The bridge was made of Sfoggaria stone; the mechanical properties of the homogenized masonry were derived based on the mechanical properties of the stone presented by Psycharis et al. (2019) and the equations by Ghiassi et al. (2019). Furthermore, the material properties of the backfill soil were considered, as stated by Forgács et al. (2020).

Modal analyses of the initial finite element model reveal that the first, third and fourth modes are in the transverse (Y) direction, the second mode is in the longitudinal (X) direction, and the fifth mode is in the vertical (Z) direction of the bridge. Since the bridge was under the service load, installing sensors on the way is not permitted. Therefore, two sides of the bridge were selected, and OSP analyses were performed. The MAC matrices as well as the sensor locations and their directions, are illustrated in Fig. 4. The results revealed that sensor placement metrices methods are not robust enough to detect the best locations by considering the MAC as a criterion. However, the off-diagonal members of the MAC matrices of the sensor elimination methods are less than 40%. The typical location in the sensor configurations is in the middle of the spandrel wall between the arches. Furthermore, the second most essential locations are the top of the arches. Based on the results from the EIM and considering the effect of kinetic energy and normal modal displacements concluded from the NKE and NMD, the locations on top of the arches which are closer to the sides of the bridge should be taken into account. Therefore, installing sensors in two configurations with a reference sensor for covering these locations is recommended.

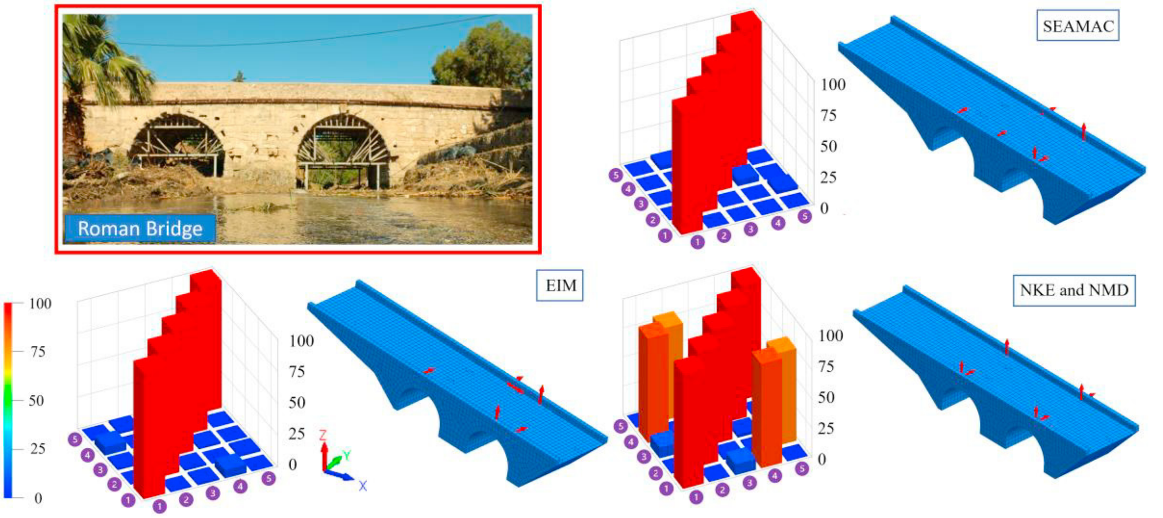

Fig. 4. The results of the OSP of the masonry arch bridge (the Roman bridge), including the MAC matrices and the prescribed locations.

3.2. Stone Masonry Tower (Slottsfjell Tower)

Slottsfjell is a three-story tower with a basement floor in Tønsberg, Norway. The tower (see Fig. 5 (a)) was dated back to 1888 on top of a rocky hill and in the area of a ruined historical castle called Tunsbergis. Fig. 5 (b) illustrates the model of the Tunsbergus castle, which was the largest castle in Norway in the 14th century and was destroyed in 1503 based on Norli (2021). The 3D finite element mesh of the tower was developed using 3D laser scanners, and details about the procedure are elaborated by Shabani, Ademi, et al. (2022). In order to investigate the effect of boundary conditions on the dynamic characteristics, as was highlighted by Salehi & Erduran (2022), two models were developed, which are the fixed base model (FB) and the model, by considering the effect of soil-structure interaction (SSI) as depicted in Fig. 5 (c) and (d), respectively. In the SSI model, the direct method has been utilized by modeling the foundation and the soil box, as elaborated by Shabani, Feyzabadi, et al. (2022). The first and the second modes of both models are transversal in X and Y directions, the third mode is the torsional mode, and the fourth and fifth modes are transversal in X and Y directions, respectively.

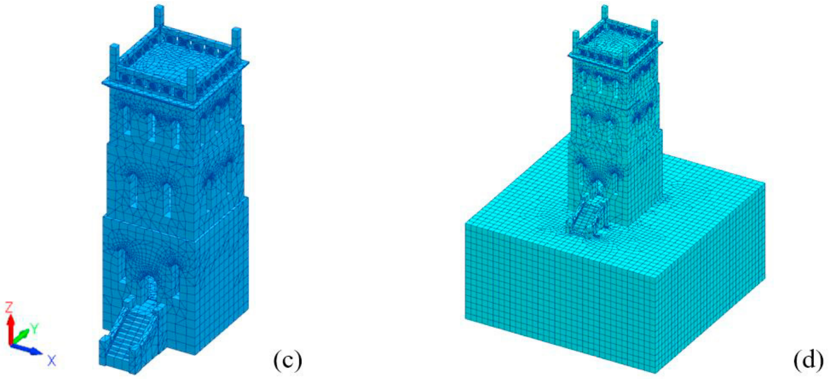

Fig. 5. (a) Slottsfjell Tower in Tønsberg (b) old Tunsberghus fortress based on Norli (2021), 3D FEM of (c) fixed-base model and (d) the model with considering SSI.

The edges of the inner sides of each floor, including the roof, were selected as the optimized candidates for installing seven sensors to perform the OSP analysis. Fig. 6 shows the optimum sensor configurations and the MAC matrix for each OSP method applied to the FB model. Results depict that the sensor elimination methods except for the EIM are robust enough to detect the best locations by considering the MAC as a criterion. The roof has allocated the largest number of sensor locations, and all methods prescribe installing sensors neither on the first floor nor in the Z direction. Based on the IGR and SEAMAC results, the second floor is as important as the third floor for sensor installation and AVT.

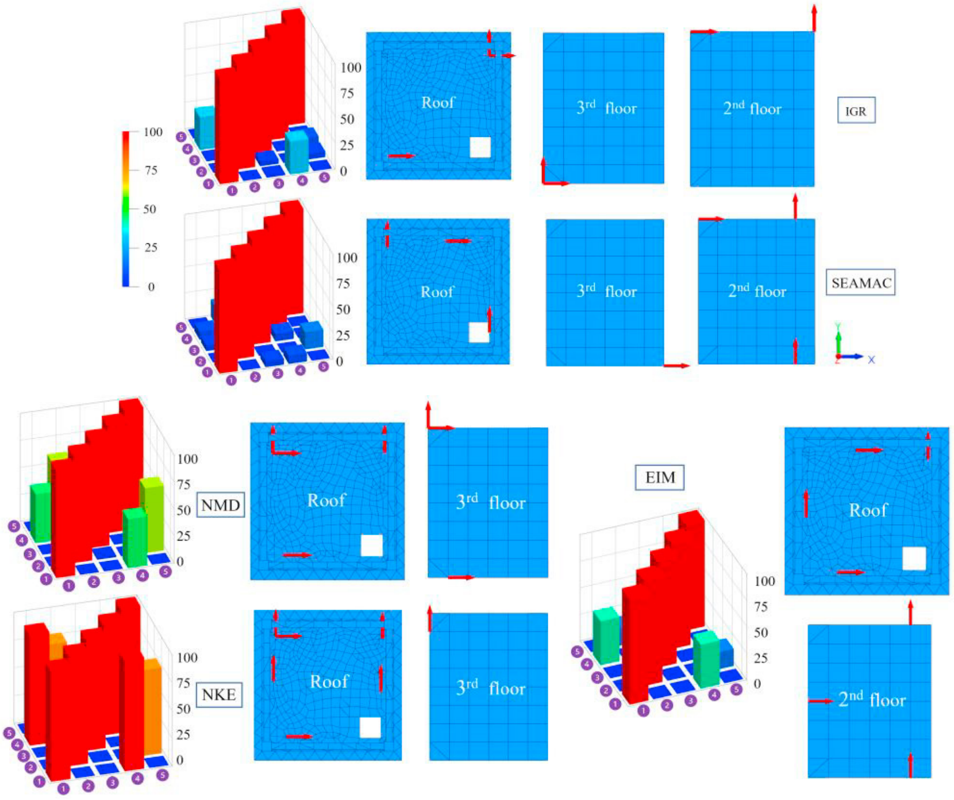

Fig. 6. The results of the OSP of the fixed-base model of the Slottsfjell tower, including the MAC matrices and the prescribed locations.

OSP of the model considering SSI was performed on the Slottsfjell tower, and the results are presented in Fig. 7 for all five methods. The MAC matrices were not changed significantly, but the leading locations were shifted from the third floor to the second floor. This could be due to the flexibility of the boundary conditions of the tower because of considering the effect of SSI. Therefore, except for the roof, the optimum locations should not necessarily be on the upper floors, and the second and third floors are the essential floors for installing the sensors.

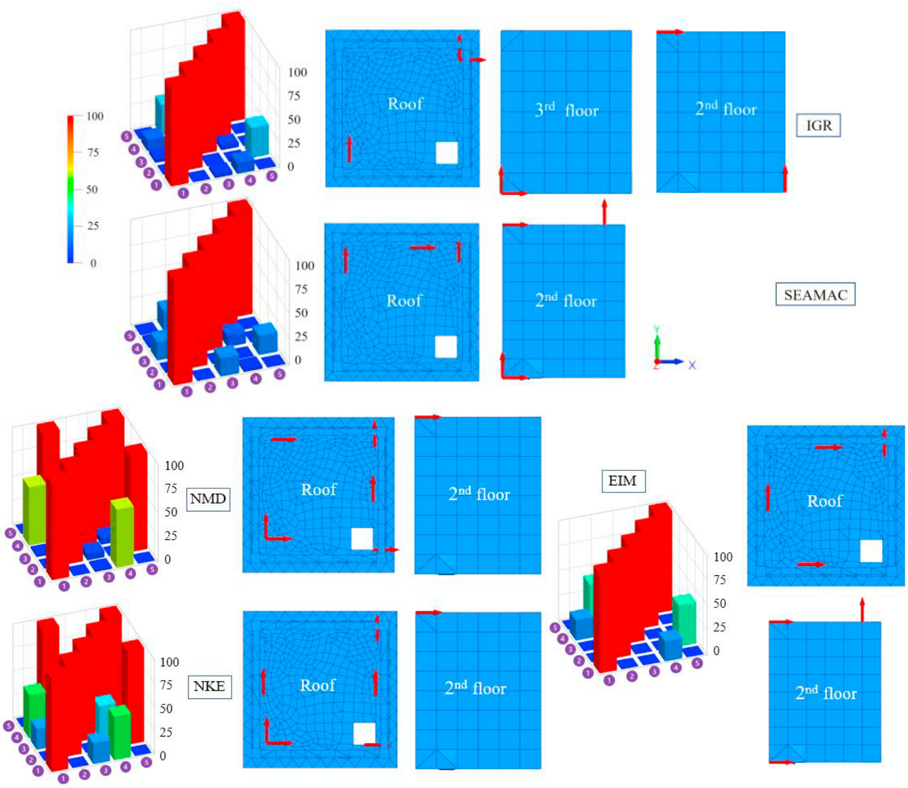

Fig. 7. The results of the OSP of the Slottsfjell tower model considering SSI, including the MAC matrices and the prescribed locations.

4. Conclusion

Identifying the optimized locations of the limited numbers of accelerometers to derive the mode shapes of structures can be done by applying the OSP methods on the FEMs with initial material properties. Since destructive tests are not permitted to define the material properties of historical structures, OSP methods are recommended before performing AVT. The application of different OSP methods on the FEMs of a stone masonry arch bridge and a stone masonry tower was investigated. The results revealed that sensor elimination methods are more robust than the sensor metrices methods by considering the MAC as a criterion. For the masonry arch bridge, the sensors should cover the locations in the middle of the spandrel walls, on top of the arches, and locations between the top of the arches and two sides of the bridge. The roof is the most important place for installing the sensors, and installing sensors on the first floor was not recommended. Furthermore, by modeling the soil box and foundation based on the direct method for considering the SSI, the MAC matrices were not changed significantly, but the candidate sensor locations were shifted from the third floor to the second floor. Thus, the sensors should cover the roof, second, and third floors, respectively. Unlike for the Slottsfjell tower, the vertical (Z) direction is crucial to be recorded for the Roman bridge. The SEAMAC is considered an efficient OSP method due to its formulation based on the numerical analysis in this study. However, in order to confirm these findings, the results of the numerical analysis should be compared to the results of the OMA, which are based on the AVT.

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