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Conceiving Meta-structures for Civil Engineering Applications

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Abstract

The concept of meta-structure is well established in the literature, and its implementations by 3D printing are typically discussed. Attempts to extend their applications to the civil engineering field found an obstacle in the significant masses that such applications would require. This contribution investigates the feasibility and the potential of a meta-structure design, which is consistent with the civil engineering requirements.

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Keywords: meta-structures, vibrations control, civil engineering

1. Introduction

Meta-structure is a term becoming very common in mechanical and civil engineering. In principle, given a structure, one has to add a further structure to obtain a meta-structure [1-2]. From this point of view, any system of structures can be referred to as a meta-structure.

When the perspective field belongs to mechanic or aerospace engineering, the added components are designed and, then, their realization can also be pursued by a 3D printer [3-4]. Applications in civil engineering, even if proposed in the literature [5-7], meet the non-minor difficulty of the significant masses usually required for the added components [8-9].

The idea on the back of a technology feasible for civil engineering applications comes from the world of vibrating barriers often adopted to mitigate vibrations induced by traffic [10], with recent extensions to other fields [11-12].

In this paper, a problem of soil structure interaction [13] is addressed, and the possibility of exploiting the well-known technology of jet grouting [14] for the implementation of the added components is investigated.

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2. Reference structural system

2.1. A soil structure interaction application

The reference problem considered in this paper is the numerical simulation of a soil-structure system, as already discussed in [11]. A homogeneous soil deposit of depth 60 m covers the bedrock and supports a structural system made of concrete and shaped as a dome, where significant nonstructural masses are located. The discretization implemented in the Marc software environment [15] and shown in Figure 1 is adopted. The first frequency of the uncoupled structure (3.712 Hz) is quite close to that of the soil body itself (3.823 Hz), resulting in quite important displacements when the bedrock is excited close to the resonance (Figure 2). When the soil and the dome are coupled, the first frequency becomes 3.656 Hz. Some response time histories are plotted in Figure 3. It is seen that for the displacements there is an amplification factor of 7.5 at the top of the soil body, while it becomes 80 at the top of the dome.

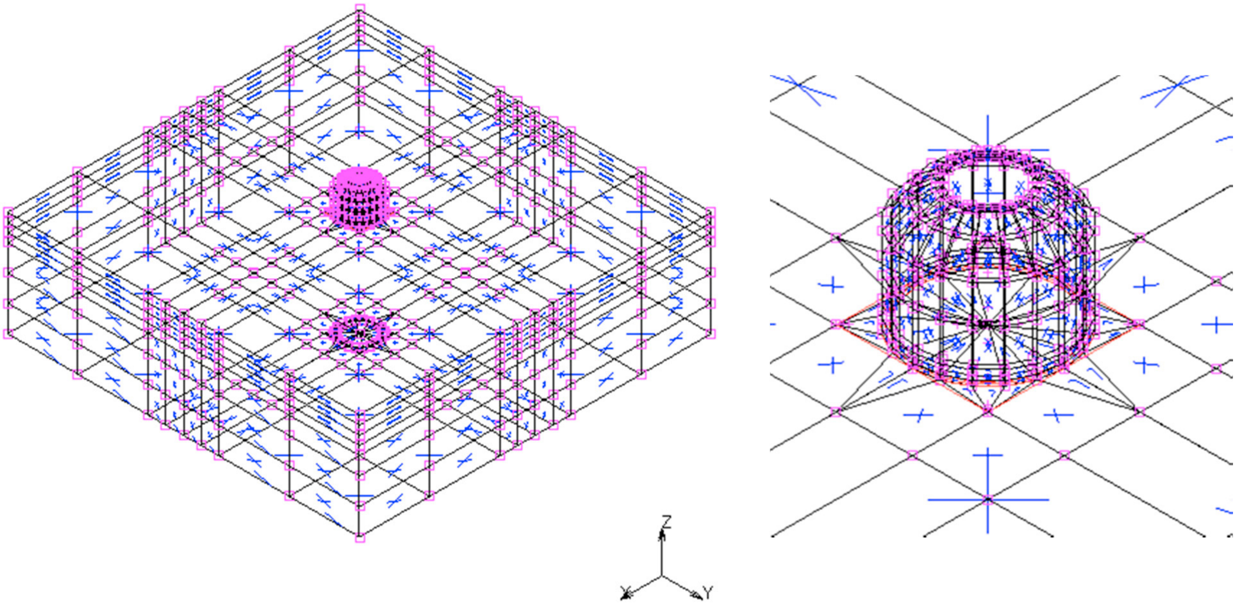

Fig. 1. The reference system

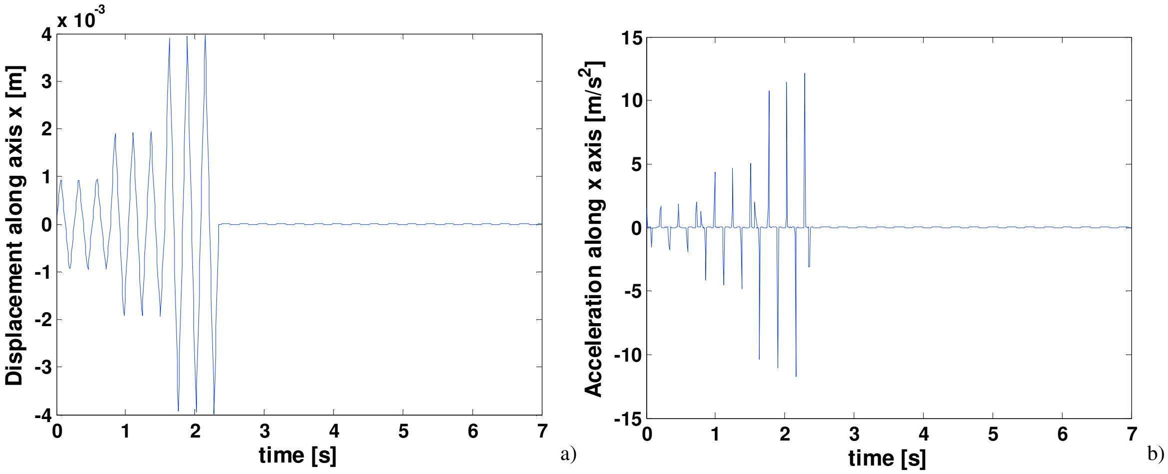

Fig. 2. Bedrock excitation along direction *x* (a) assigned displacement and (b) acceleration (as from the FEM code).

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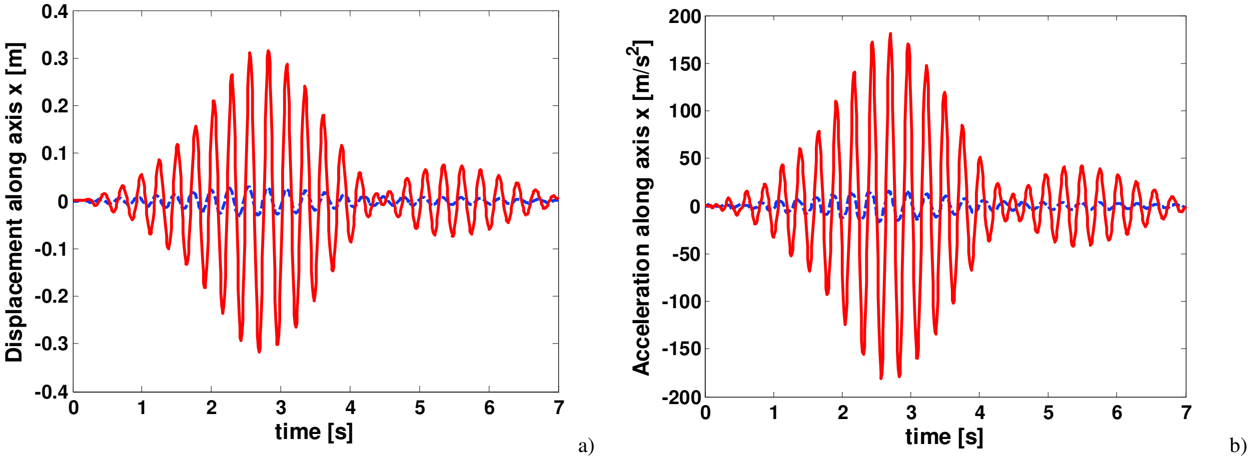

Fig. 3. System response: a) displacement and b) acceleration along axis *x*. The solid line refers to the top of the dome, the dashed line to the top of the soil body.

It is worth mentioning that the maximum assigned displacement is only 4 mm. However, quite significant values of the acceleration are involved due to the frequency value and to the saw-tooth profile. The performed dynamic transient analyses are linear, and therefore the focus will be placed on the amplification factors.

2.2. Vibration mitigation via base isolation

A standard approach to vibration mitigation would exploit base isolation. For instance, by replacing the bottom circle of elements of the structure in Figure 1 with an orthotropic material simulating the combined effects of alternate steel and rubber disk layers, the frequency of the dome drops to 0.26 Hz. and the obtained global response is quite convenient (Figure 4).

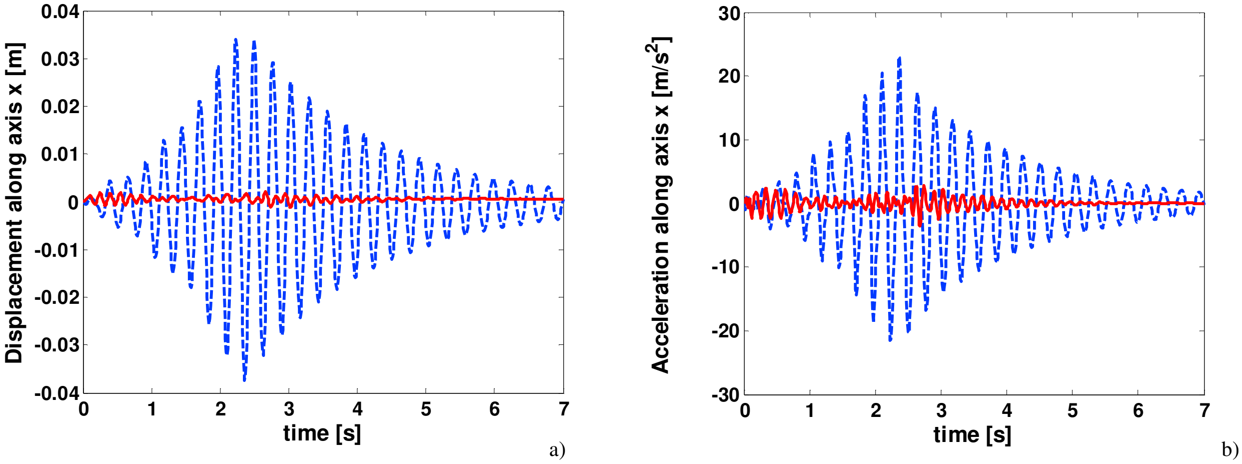

Fig. 4. Isolated system response: a) displacement and b) acceleration along axis *x*. The solid line refers to the top of the isolating layer in a) and to the top of the dome. The dashed line refers to the top of the soil body.

However, this strategy requires working under an existing structure, i.e., supporting or suspending it in some way, which could be unfeasible when large non structural masses are involved.

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3. Jet grouting and meta-structure

Jet grouting is a mature technology used to increase the resistance and the stiffness of soils. It requires open space for the operating machine on the entire surface covering the volume of soil that must be treated. A depth of 15 m is easily afforded. In the considered case study, this involves the three top layers in the soil discretization. It is worth mentioning that one can alter the stiffness by either increasing or decreasing it. The latter solution would suggest to implement a sort of base isolation, but this is in general not possible since it would require to interrupt the continuity between the soil and the structure foundation. Therefore, only the cases improving the stiffness of a limited part of soil are investigated.

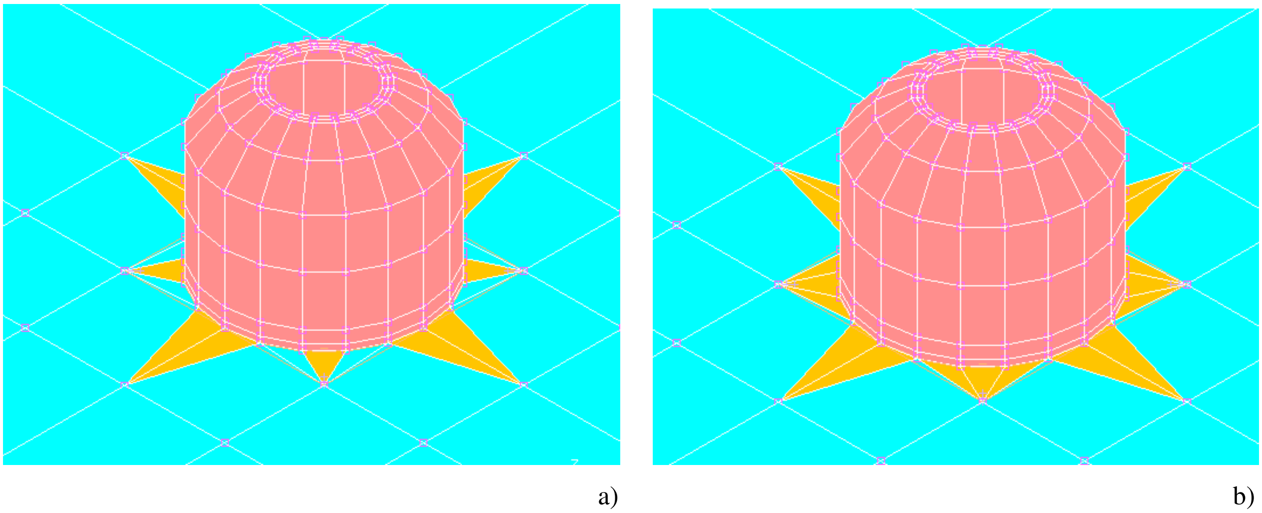
a) b)

Fig. 5. Two scenarios for the jet grouting application: a) three layers of soil below the shaded triangles see the stiffness increased by a factor of ten; b) additional volume is considered along the two lines rotated of 45° with respect to the reference axes.

3.1. Improving stiffness nearby the structure

Two scenarios are considered as sketched in Figure 5. In both cases, the interested soil volume covers a depth of 15 m corresponding to three layers of elements in the discretized model. In the first case, the soil stiffness is increased by a factor of 10 in the elements surrounding the structure that are located below the shaded. triangles in Figure 5a. In the second case, the stiffness increase interests an additional volume, as depicted in Figure 5b. The main response features are summarized in Table 1. The response time histories are shown in Figure 6 for the case of Fig. 5b. They show how conveniently the original system response in Figure 3 modifies .

As an extreme scenario, the upgrade in Fig. 5b) is enriched by increasing the volume of the first soil layer (5 m) with improved stiffness so that its cross-section is a hollow square of 40m by 40m surrounding the structure . The results in Table 1 give an idea of the marginal, but costly, advantage achieved.

3.2. Adding a stiffener barrier

An attempt to add stiffness far from the structure, where technologically easier, is also developed by inserting a barrier all around the system at a minimal distance of 10 m (Figure 7). In this case, the depth is still of three layers and the soil stiffness is still increased by a factor of 10. Indeed, the common target of the scenarios described in this subsection and in 3.1 is to shift the system frequency to higher values, i.e., to move out from the resonance starting condition, as reported by the results in Table 1.

4. Discussion of the results

A comparison of the amplification factors obtained in the original problem and in the four scenarios built by

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increasing the stiffness of assigned volumes of soil is also given in Table 1. The amplification factors are the target of the design process. It is seen that adding more and more volume, but as much closer to the structure, it is possible to pursue a lower amplification factor in both displacement and acceleration. Also the peak absolute displacement at the soil node under the structure (from which the amplification factor is computed) changes.

In the next case the barrier is replaced by an empty gap, just to check the consequence of such a choice. It is seen that the absolute values of the displacement decrease, but the amplification factor are practically unmodified.

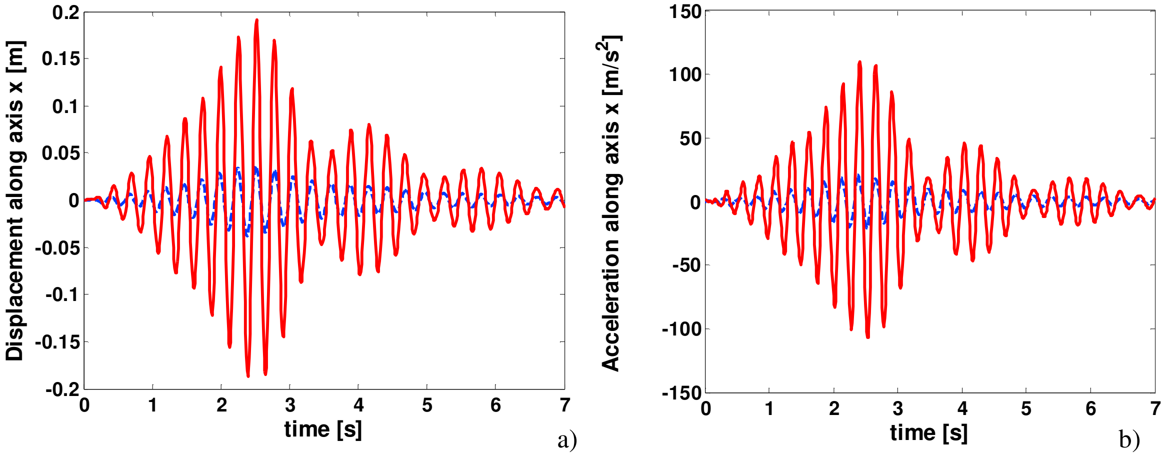

Fig. 6. System response for the upgrade in Fig.5b): a) displacement and b) acceleration along axis *x*. The solid line refers to the top of the dome, the dashed line to the top of the soil body.

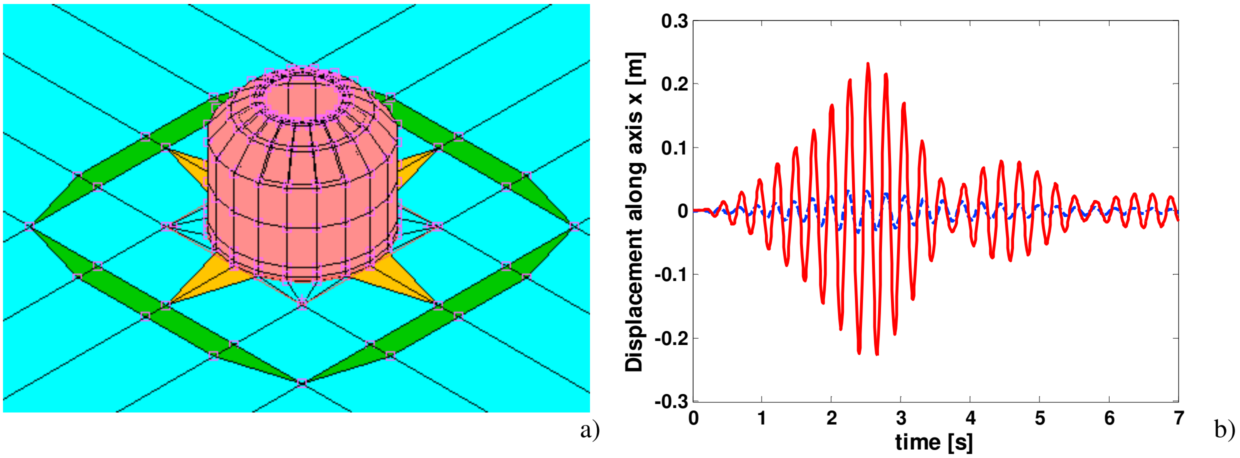

Fig. 7. Building a barrier surrounding the structure (a); displacement response (b). The solid line refers to the top of the dome, the dashed line to the top of the soil body.

Table 1. Changes in the main response features.

	Soil absolute displacement peak [cm]	Displacement amplification factor	Acceleration amplification factor	Frequency [Hz.]
Original structure	3.06	10.36	11.03	3.656
Case of Fig. 5a	3.60	5.92	6.19	3.737
Case of Fig. 5b	3.76	5.25	5.24	3.746
Extreme scenario	3.62	4.48	4.68	3.757
Barrier	3.36	6.89	7.24	3.732
Gap only	2.45	9.59	10.20	3.510

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5. Conclusions

In this paper, the potential of jet grouting [15] for the realization of meta-structures consistent with civil engineering applications is investigated. A soil-structure interaction problem is considered where the structure under investigation is surrounded by open space so that the jet grouting can be implemented without obstacles. For the considered case, a vibration mitigation via base isolation is made difficult by the large masses involved, both in terms of installation on an existing structure and the large values of relative displacement that the isolating material would be required to undergo.

This paper shows how enhancing the soil stiffness all around the structure, but not below it, permits to achieve some reduction of both displacements and accelerations by shifting the system frequency to higher values.

Future developments will introduce convenient periodicity features into the added structures, which, together with the core structure, form the meta-structure.

Acknowledgements

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