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THE EFFECT OF GROUT INJECTIONS ON THE SEISMIC RESPONSE OF STONE MASONRY WALLS

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Abstract. *The paper regards the behavior of stone masonry walls against out-of-plane seismic actions. In this context, the effectiveness of grout injections is experimentally explored, with respect to soil–foundation–structure interaction (SFSI). Wall–footing specimens of reduced scale (1:3), simulating typical three-leaf stone masonry walls, were tested before and after the application of grouts. The walls consisted of rubble limestone, lime-pozzolan based mortar, and loose infill material with an approximate 40%-45% voids ratio. So as to ensure compatibility with the aforementioned constitutive materials, hydraulic lime pozzolanic grouts were employed for the rehabilitation of the walls. As far as the interaction between the wall–footing specimens and the soil is concerned, the following two cases were considered: (i) the specimens were founded on a rigid base, thereby completely ignoring the role of SFSI effects, and (ii) the specimens were founded directly on a dry sand substratum of controllable relative density (D_r). In order to further assess the influence of soil resilience, idealized soil deposits of both dense sand (D_r = 92%) and loose sand (D_r = 33%) were modelled. The experimental results are presented and discussed mainly in terms of observed failure modes, force–displacement response, footing settlement–rotation response, and energy dissipation. As expected, the technique of grout injections resulted in the improvement of the homogeneity and the structural integrity of the masonry (voids and cracks were filled, internal cohesion was increased). It is shown that the performance of the specimens was significantly affected by soil–foundation–structure interaction effects, due to the activation of specific non-linear mechanisms. Interestingly, as indicated by the results the effectiveness level of the grout injections actually varies, depending on whether the rehabilitated specimen was founded on a rigid base, on dense sand, or on loose sand respectively.*

1 INTRODUCTION

The paper studies the seismic performance of cultural heritage constructions, while taking into consideration the interaction between soil, foundation and superstructure. More specifically, the out-of-plane response of three-leaf stone masonry walls before and after rehabilitation is experimentally examined. In several European countries such as Greece, Italy and Slovenia, three-leaf stone masonry is commonly met upon historic structures and monuments. The cross-section of the specific structural typology comprises of two load-bearing external leaves and a poor quality incoherent inner leaf. The external leaves are constructed with stones and binding mortar as individual parallel walls, whereas, the inner core consists of small stones and stone fragments bonded together by mortar. In general, the wall cross-section does not behave in a monolithic way due to the lack of transversal connection between the separate leaves. The aforementioned features result in reduced lateral resistance, thus rendering three-leaf stone masonry particularly vulnerable against out-of-plane seismic actions. The most commonly observed failure mechanisms include the separation and detachment of one of the external leaves, as well as the (partial) out-of-plane collapse of the wall [1].

In recent years increased scientific interest has been raised around the subject of soil–foundation–superstructure interaction (usually referred to with the term SFSI). It is reasonable to suggest that SFSI can have a substantial effect on the seismic performance of a construction. What mainly differentiates the conventional rigid base assumption from the concept of SFSI is the fact that additional degrees of freedom are introduced in the problem when taking account of the interaction with the soil. Particularly for constructions with shallow foundations, as is the case for historic stone masonry structures, the following non-linear mechanisms can be observed: (i) foundation rocking, (ii) sliding along the soil–foundation interface and (iii) mobilization of soil bearing capacity. Clearly, the first two mechanisms are associated with the nonlinearity of geometry, while the third one is related to material nonlinearity.

The need to conduct the specific research arose from the lack of equivalent published data. Previous studies have mainly emphasized on the out-of-plane testing of brick and block masonry, without even remotely addressing the issue of the interaction with the soil (e.g., [2]-[5]). The obtained experimental results serve in enabling the development and calibration of computational models. What's more they are vital in providing insights into the complex subject of the out-of-plane response of stone masonry, with due consideration to SFSI effects.

2 TEST PROCEDURE

The examined wall–footing specimens are 1:3 scaled models of the structural components met upon typical three-leaf stone masonry historical structures. The masonry wall cross-section consists of three equal width leaves (i.e., $t_e = t_i = ⅓\, t_w$), with no transversal connection provided between them (see Figure 1a). The external leaves comprise of rubble limestone and lime-pozzolan based mortar. Whereas, the infill material is made of limestone fragments mixed with the same binding mortar. A voids ratio of 40%-45% was approximately achieved by gradually pouring the infill material, without compaction, into the gap formed between the external layers. Mix proportions and material characterization data, as derived from in-laboratory tests, can be found in [6]. The geometric dimensions (width, length, height) of the masonry wall are as follows: t_w = 0.20m, ℓ_w = 0.50m and h_w = 1.00m. While, the respective dimensions of the concrete spread footing are: t_f = 0.30m, ℓ_f = 0.50m and h_f = 0.10m. As is customary for stone masonry, the footing runs across the wall length and expands 0.05m, on either side, beyond its base.

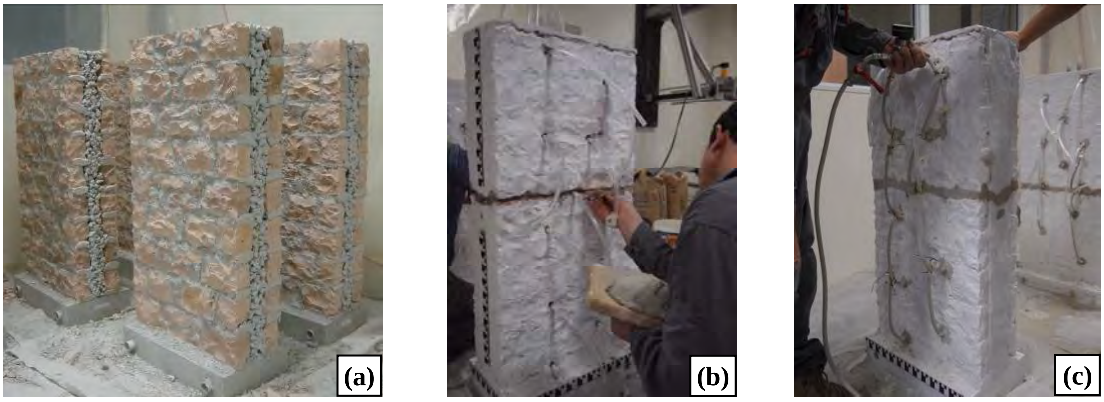

Figure 1: Wall–footing specimens: (a) as-built, (b) during the application of deep repointing, and (c) during the application of grout injections.

The intervention techniques described herein were selected while taking into consideration the masonry typology and the type of loading under investigation. More specifically, as can be seen in Figures 1b and 1c respectively, deep repointing was applied prior to the rehabilitation of the masonry wall via the application of grout injections. A brief overview of the specific intervention techniques is given in the paragraphs hereafter.

Deep repointing is a mild remedial method often applied in conjunction with masonry grouting. It involves removing part of the existing mortar from the masonry joints (in a considerable depth) and replacing it with a mechanically improved repair mortar. The latter one must present physicochemical compatibility with the in situ constituent materials. In this case, a natural hydraulic lime based repointing mortar was used.

Grouting is commonly employed for the rehabilitation of three-leaf stone masonry [7]-[8]. It is well known that the particular masonry type is characterized by the high percentage of internal voids and the lack of continuity within its thickness. Grout injections aim at consolidating the masonry cross-section by filling the existing voids and cracks and increasing the internal cohesion; thus enhancing its structural integrity. The applied grout mixture has to satisfy a number of criteria in order to assure compatibility with the existing materials and suitability for application on historic masonries. This is extremely important, given the fact that the technique is irreversible. A natural hydraulic lime pozzolanic grout was designed for the scopes of this research project. As proven by in-laboratory tests (results can be found in [6]), the selected grout composition meets the injectability requirements (i.e., penetrability, fluidity, stability), and is mechanically efficient for the rehabilitation of the three-leaf stone masonry walls.

Even though the paper is dedicated in the effect of grouting, for reasons of completeness, it should be mentioned that within the overall project an additional intervention technique was also examined. Namely, the possibility of accomplishing out-of-plane strengthening by introducing post-tensioning to the wall. More details regarding the designed post-tensioning system can be found in [6] and [9].

The main features of the experimental project are summarized in Table 1. A series of static pushover out-of-plane tests were performed in the National Technical University of Athens (NTUA) Laboratory of Soil Mechanics. The specimens were subjected to monotonic and cyclic displacement-controlled horizontal loading, applied at wall mid-height by means of a servo-electric screw-jack actuator. A slow increment rate of 0.2 mm/s was kept throughout the testing sequence.

The role of SFSI was examined by founding the wall–footing specimens either on a rigid base, or directly on a homogeneous layer of dry sand of controllable relative density D_r. The sand was pluviated inside a transparent rigid soil container with the help of an electronically-controlled sand raining system. An industrially produced fine and uniform quartz sand with median grain size D_{50} = 0.15mm and uniformity coefficient C_u = 1.42 (dry Longstone sand) was used in the tests. Its main characteristics, as obtained by in-laboratory tests, have been documented in [10]. To further assess the parameter of soil resilience, two idealized soil layers were modelled: (i) dense sand of D_r = 92% (corresponding to ideal soil conditions), and (ii) loose sand of D_r = 33% (corresponding to poor soil conditions).

A load-cell was attached to the pushover apparatus in order to measure the force applied on the specimen while imposing the prescribed displacements. Horizontal and vertical displacements were recorded through nine wire displacement transducers placed at key locations; thus allowing for the wall–footing specimen's overall response to be supervised. The soil–footing interface was constantly monitored through a high-definition digital camera. After the test, the specimen was carefully removed from the test-rig and laser displacement transducers were used to scan the soil surface. That way the post-test soil deformation profile was obtained. All instruments were connected to a digital data acquisition system.

Table 1: Main features of the experimental project.

Loading	Masonry wall condition	Soil–foundation–structure interaction
Monotonic	As-built	Specimen founded on a rigid base
	Rehabilitated with grout injections	Specimen founded on dense sand (D_r = 92%)
Cyclic	Strengthened via post-tensioning	Specimen founded on loose sand (D_r = 33%)

3 DISCUSSION OF OBTAINED RESULTS

An overview of the experimental results, before and after interventions, is presented in this section. A uniformity of the main force-displacement response trends can easily be perceived by comparing the results obtained from monotonic and cyclic tests. A noticeable change in wall stiffness was recorded at force levels associated with initial cracking (F_{cr}), clearly indicating the end of the linear elastic stage. Over the course of the tests, post-cracking stiffness degradation was observed due to accumulated damage.

The out-of-plane response of the wall–footing specimens was substantially affected by soil–foundation–structure interaction. The non-linear mechanisms of footing rocking and soil bearing capacity mobilization were mainly manifested during the tests. The fact that foundation rocking prevailed over sliding is attributed to the slenderness of the examined specimens. As expected, the interaction with the soil led to higher levels of energy dissipation. Qualitative differences were observed in the specimen behavior depending on soil resilience. Interestingly, however, the residual strength of the wall was similar regardless of the soil conditions.

In the case of dense sand (D_r = 92%), the specimen response was characterized by footing uplifting at each loading cycle, which led to a reduction of its effective width. Successive cycles of footing rocking resulted in the loss of contact with the underlying soil near the footing edges. The specific phenomenon was confirmed by the arc-shaped soil formation beneath the footing, which was recorded in the soil deformation profile with the help of laser displacement transducers.

In the case of loose sand (D_r = 33%), instead, the response was sinking-dominated. Extensive soil yielding was observed, which resulted in the accumulation of considerable footing settlement. As displayed in Figure 2, the overall footing settlement (w_f) was approximately three times higher than the one measured for dense sand (note that settlement is denoted positive). On the other hand, the measured footing rotation (θ_f) was of the same magnitude for both dense sand and loose sand. More details concerning the role of SFSI effects can be found in [9].

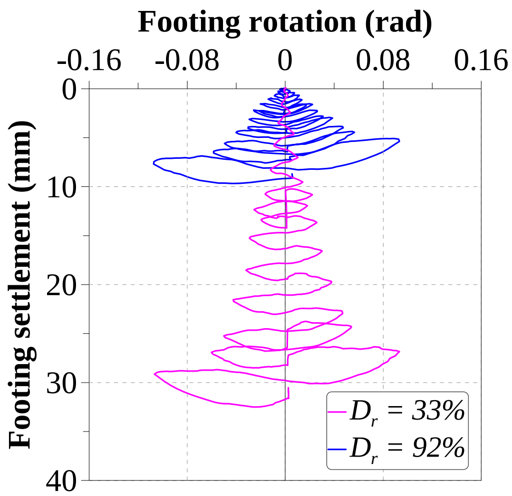

Figure 2: Footing settlement–rotation response: comparison between dense sand (D_r =92%) and loose sand (D_r = 33%).

The rehabilitation technique of grout injections proved to be highly effective, as the overall response of the grouted specimens was significantly improved. Internal voids and gaps were completely filled, leading to mass homogenization of the three-leaf stone masonry and the enhancement of its internal cohesion. It should be noted that, after test completion, the successful application of grouts was additionally confirmed by the visual inspection of the consolidated wall cross-section.

Apart from the substantial increase in the out-of-plane bearing capacity of the wall after grouting, a noticeable delay in cracking manifestation was also recorded. Given the fact that common displacement protocols were used for all tests, the magnitude of the aforementioned delay can be perceived simply by comparing the respective loading cycle number (e.g. cracking onset was suspended from cycle no. 2 to cycle no. 8).

Interestingly enough, the results indicate that the effectiveness level of grout injections itself varies depending on whether the rehabilitated specimen was founded on a rigid base or on a dry sand layer (i.e., on whether or not SFSI was considered). For example, in the case of the rigid base, the specimen's resistance after grouting was increased by approximately 70% (with respect to the corresponding as-built strength of 1.92kN). Whereas, in the case of loose sand, the beneficial effect of grouting was more pronounced and resulted in an approximate 130% capacity increase (in regards with the corresponding as-built capacity of 1.43kN).

Once again for reasons of completeness, it is worth mentioning that the experimental findings verified post-tensioning can be used to successfully strengthen stone masonry walls against out-of-plane actions. As shown in [9], the addition of the post-tensioning system significantly increased the moment capacity of the wall, thus enabling it to: (i) resist the respective maximum force attained by the as-built wall (namely, 5.21kN) while remaining in the elastic regime, (ii) sustain double the maximum force withstood before strengthening (specifically, 10.79kN), and (iii) maintain a residual strength near the magnitude of the ultimate wall capacity recorded before strengthening.

Generally, failure mechanisms associated with one-way vertical out-of-plane bending of the masonry wall were observed during the tests. The limestone units themselves continued to remain elastic even after the mortar joints had begun to crush. Horizontal flexural tensile cracks formed along the mortar joints near the wall mid-height (i.e., area ranging between $0.45h_w$ and $0.55h_w$), where the extreme fibers of the cross-section reached their ultimate capacity due to the development of high tensile strain.

In the case of cyclic tests, consecutive loading cycles were associated with further crack widening and propagation. The walls suffered severe damage as they were pushed to out-of-plane displacements (Δ_{max}) of almost the same magnitude as the width of the masonry external leaf (i.e., ⅓ t_w). As already mentioned, a noticeable delay in the onset and progression of cracking was observed after interventions. Other than that, rehabilitation through grout injections did not modify the basic failure mode of the wall (see Figure 3).

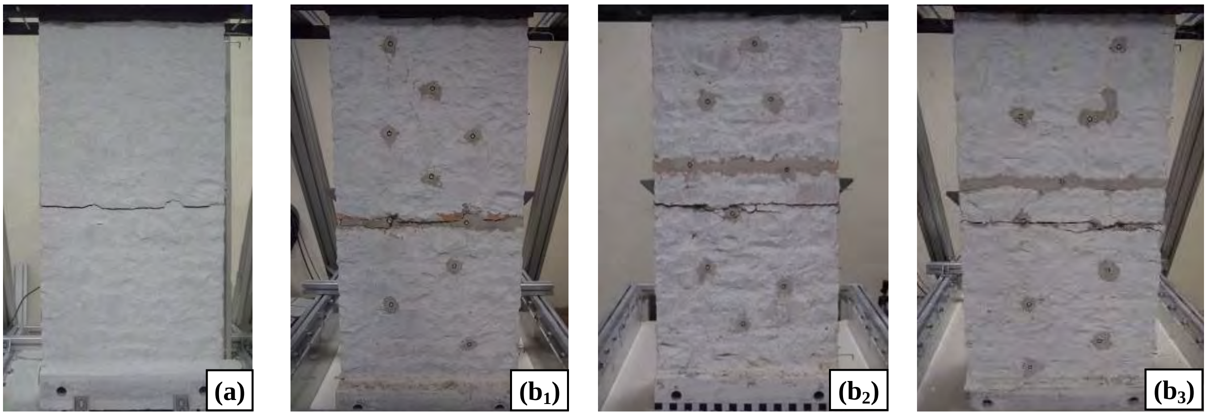

Figure 3: Typical failure modes observed: (a) before grouting, and after grouting for (b_1) specimen founded on a rigid base, (b_2) specimen founded on dense sand, and (b_3) specimen founded on loose sand.

4 CONCLUSIONS

- The response of historic three-leaf stone masonry walls, before and after interventions, was presented. The influence of grout injections, combined with deep repointing, was mainly examined. Additionally, the parameter of soil–foundation–structure interaction was investigated by founding the masonry wall–footing specimens directly on a dry sand layer of desirable relative density.

- It was shown that the specimen performance was significantly influenced by SFSI effects, due to the manifestation of additional non-linear mechanisms (i.e., combined footing rocking and soil bearing capacity mobilization). The aforementioned mechanisms resulted in greater energy dissipation levels. In the case of dense sand (D_r = 92%) footing rocking/uplifting prevailed and led to the reduction of the footing's effective width. For loose sand (D_r = 33%) the response was governed by sinking, leading in the accumulation of treble settlement. Despite the obvious behavioral disparity between dense and loose sand, however, the obtained results suggest that the magnitude of the wall's residual strength was independent of the soil stiffness.

- Rehabilitation by means of natural hydraulic lime pozzolanic grout injections proved to be highly effective, as it led to substantial improvement of the out-of-plane strength of the specimens. Interestingly, the actual efficacy level of the technique seems to vary depending on whether or not SFSI was taken into account. When the rehabilitated specimen was founded on a rigid base its ultimate capacity was improved by 70%. In the extreme opposite case in terms of substratum stiffness (i.e., when the specimen was founded on loose sand) a 130% increase of resistance was achieved.

- Crack formation was clearly delayed after rehabilitation. During cyclic tests the onset of cracking was actually postponed for several loading cycles in comparison with the corresponding as-built tests. The application of grout injections did not modify the wall's failure mechanism.

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