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Field trials on soft grouting barriers to mitigate vibrations effects

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ABSTRACT
The use of soft buried barriers to mitigate the effects of vibrations has been deeply analysed in literature, showing that their effectiveness depends on dynamic impedance ratio and on the barriers' geometry. However, most times the problem of the physical and mechanical properties to be given to the barrier is by-passed. This paper proposes to deal with barriers made of an innovative material, a special kind of Super Absorbing Polymer (SAP), easy and cheap to find and environmentally friendly. In particular, a field trial test has been carried out, in which an inverted pyramid barrier and a linear barrier have been created with a 100% SAP filling. The site was fully instrumented and carefully investigated, and vibration tests were carried out. It was shown that the barriers were able to largely attenuate the vibrations, thanks to their mechanical and physical properties.

1 INTRODUCTION

Technological interventions into the ground to mitigate the effects of vibrations have been employed in the past, mostly with reference to the effects of anthropic actions (e.g. surface vibrations induced by vehicles and rail-bound traffic). To this aim, several and different solutions have been studied, all with the goal of modifying the impedance ratio α, defined as the dimensionless ratio between the dynamic impedance of the natural and of the treated soil ($\alpha = \rho_s V_s / \rho_g V_g$): for instance, creating a stiff layer (e.g. Chouw and Schmid, 1992; Kellezi, 2011) or installing vertical wave absorbing barriers close to the vibration source (e.g. Massarsch, 2003, 2005).

For buildings, the concept of vibration screening was developed by several authors (Woods, 1968; Liao and Sangrey, 1978; Kirtas et al. 2009a; Kirtas and Pitilakis 2009b). Most times the problem of the physical and mechanical properties to be given to the barrier is by-passed considering the best possible option, which is the adoption of air inflated balloons. However, such barriers may easily lose their effectiveness in time, thus having little or no practical interest.

Recently, Nappa et al. (2016) showed in both numerical and experimental analyses the effectiveness of a deep horizontal layer of softened soil to reduce earthquake-induced ground shaking at surface. Flora et al. (2016) have explored the possibility of implementing a 'soft barrier' as a continuous, thin grouted curtain isolating a portion of soil and the building to protect. They have studied a similar treatment in the form of a rectangular 'caisson' with soft walls and base, also suggesting as an alternative a V-shape treatment. The latter is easier to be formed in situ with inclined and partially overlapped drillings, using an innovative material, a special kind of Super Absorbing Polymer (SAP), easy and cheap to find and environmentally friendly. It is a powder that can absorb and retain extremely large amounts of water due to the ionic concentration of the aqueous solution. In deionized and distilled water, the SAP adopted in this research may absorb 500 times its weight. Upon wetting, the particles become extremely deformable and with a gelatinous aspect. SAP may be easily mixed in situ with the soil, to reach as a result a soft soil-SAP mixture having the desired low value of the dynamic impedance. In their work, the authors have shown that by mixing this SAP with the in situ soil in different percentages, a soft mixture can be obtained having a shear wave velocity much lower than that of the original soil.

This paper presents an application of such a soft barrier to mitigate the effects of surface vibrations. In particular, a field trial test has been carried out, in which a classic linear barrier and an inverted pyramid barrier (as an evolution of the V-shaped proposed by Flora et al., 2016) have been created with a 100% SAP filling. The site was fully instrumented and carefully investigated, and vibration tests were carried out. The experimental measurements results have been compared with those of preliminary numerical calculations, aimed at designing the trial, as shown in the following.

2 GROUND CONDITIONS

The case study site is located in a suburban area of Naples, Italy (Figure 1). Ground conditions mainly consists of pyroclastic gravelly and silty sand above a deep groundwater level.

Figure 1. Test site localization

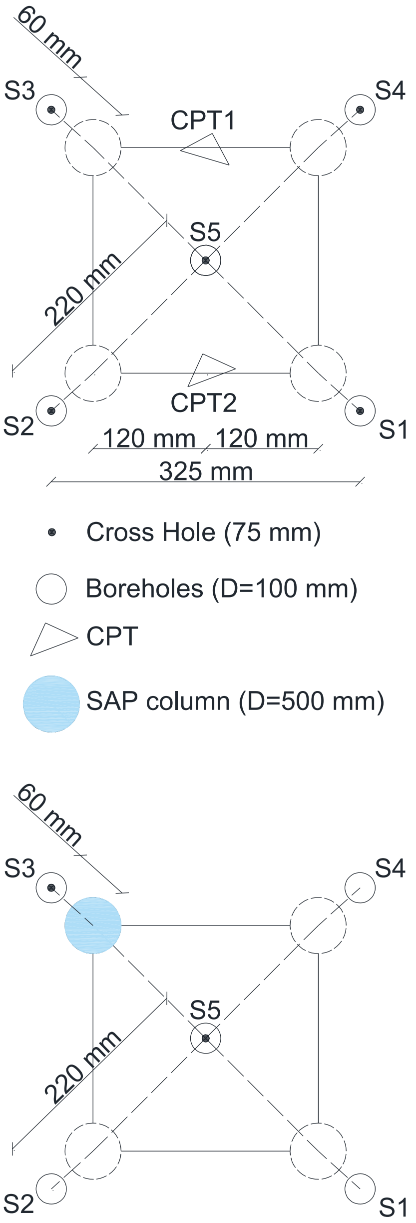


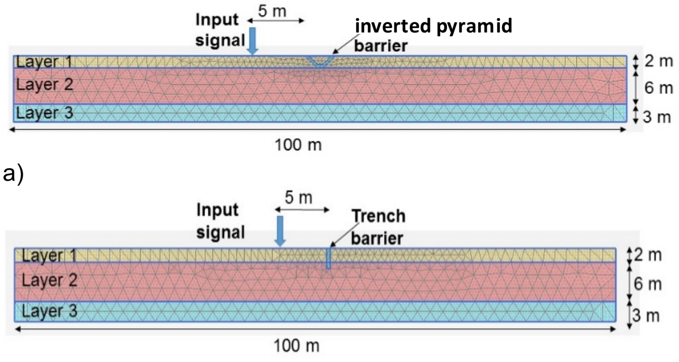
Figure 2. Testing for ground characterization

The mechanical properties of the local soil were determined prior to testing. The layout of in-situ testing is shown in Figure 2.

Five boreholes were drilled, very closely spaced, according to the layout of Figure 2a, up to a depth of 13 m. Two CPT tests and four cross-hole tests were also carried out (Figure 2a). The latter were performed by lowering a source down each of the vertex boreholes and a receiving geophone in the central hole. Later, a column made by SAP material was created between boreholes S5 and S3 and a further cross hole test was performed across the SAP column in place, to evaluate the shear wave velocity of the SAP material. This is equal to 27 m/s.

3 PRELIMINARY NUMERICAL ANALYSES

In order to design the experimental trial, a number of preliminary finite element analyses were carried out using Plaxis (Brinkgreve et al., 2015). For simplicity, these analyses were in plane strain and with harmonic input signals similar to those applied later in the tests.
The geometry of both field tests was reproduced, considering the actual layering of the site (Fig 3a,b).



b)
Figure 3. Numerical models; a) inverted pyramid barrier, b) trench barrier

The soil and the polymer were characterized by a Mohr Coulomb constitutive model. The model parameters for the soil were extracted from in situ testing results and they are reported in Table 1.

Table 1. Parameters of the materials adopted in Plaxis

Material	φ (°)	E (kN/m^3)	G(kN/m^3)
Layer 1	28	183900	76610
Layer 2	35	114700	40960
Layer 3	28	151900	54260
SAP	10	2228	743.1

Bottom and right dynamic boundaries of the model are set to be *viscous*. . The small-strain damping of the sand (D_0) was assumed equal to 0.5%. It was modelled through the Rayleigh formulation, through the coefficients α_R and β_R, estimated using the "double frequency approach" suggested by Park and Hashash (2004). Harmonic signals were used, varying the amplitude and the frequency in a range between 10 Hz and 20 Hz. The results in terms of ratio η, between the maximum values of the vertical component of acceleration time history with and without the barrier, for the signal characterized by 10 Hz frequency and 0. 5 g in amplitude , are plotted in Figure 4a,b, with respect to the distance from the source. From preliminary analyses, both the barriers seem to cause significantly reduction of the soil vibration. Inverted pyramid barrier gives a reduction efficiency of about 70% while the trench barrier of about 40%.

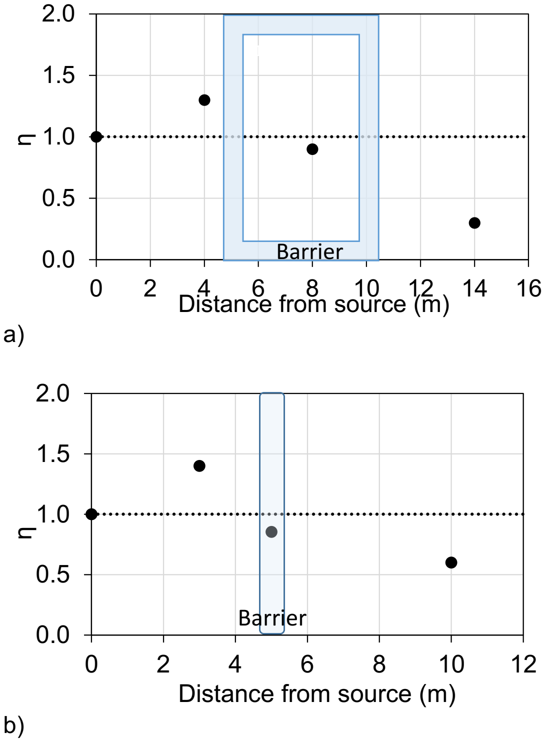


Figure 4. Efficiency ratio; a) inverted pyramid barrier, b) trench barrier

Table 3. Results of parametric analyses

Sinusoidal input		Inverted pyramid barrier			Trench barrier		
f (Hz)	A (m/s^2)	η	$\eta_{average}$	$\eta_{st.deviation}$	η	$\eta_{average}$	$\eta_{st.deviation}$
10	1	0.65	0.65	0.18	0.76	0.62	0.24
	5	0.99			0.74		
20	1	0.81			0.86		
	5	0.67			0.75		
30	1	0.65			0.90		
	5	0.74			0.39		
40	1	0.34			0.87		
	5	0.44			0.33		
50	1	0.77			0.28		
	5	0.48			0.32		

The results of all the analyses conducted, varying the amplitude and the frequency of the sinusoidal signal, are summarized in Table 2. Since vibration isolation was expected behind the trench, amplitude reduction ratios for each numerical simulation were calculated at point after the barrier. The average peak ratio $\eta_{average}$ was evaluated for both of the barriers. Averagely 40% of reduction of the vibration amplitude was obtained.

4 EXPERIMENTAL ACTIVITY

4.1 Field testing layout

Two barriers were created on site as shown in Figure 5. The source was placed between the two barriers at small distance from both of them (5 m), in order to use the barrier as an active isolation system.

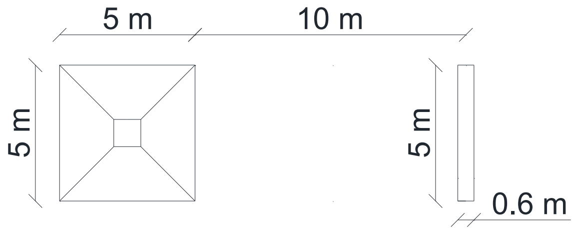


Figure 5. Layout of barriers in plan: (a) inverted pyramid barrier and (b) linear barrier.

The first barrier was created from a 2 m deep pit with inverted pyramid shape (Figure 6b), with a footprint of 5 m x 5 m at the ground surface. The hydrated polymer was put in bags, placed along the 45-degree slopes at the boundaries of the pit. Finally, the excavation was filled with the soil (Figure 6a). The average thickness of the barrier after completion was about 0.5 m.

The second barrier was an in-filled trench, 5 m long, 3 m deep, and 0.6 m thick; it was located 10 m far from the inverted pyramid barrier (Figure 6b). Thanks to suction in the unsaturated silty sand, the trench walls were stable in the short term. Hence, the hydrated polymer was placed directly in the trench, without using bags (Figure 4b).

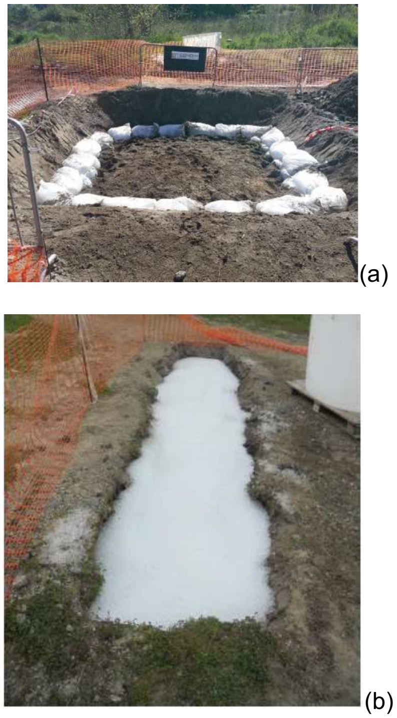


Figure 6. Photos of barriers: (a) inverted pyramid barrier and (b) linear barrier.

4.2 Testing equipment

A vibrodyne shaker, which induces a sinusoidal motion, was used as a stationary vibration source to produce harmonic force of maximum amplitude of 710N in vertical direction in a frequency range of practical importance of 10–20 Hz.

A concrete surface footing (0.80 m x 0.80 m x 0.80 m) was constructed at distance of 5 m from both of the barriers, to guarantee an effective transmission of the waves. The vibrodyne is mounted and placed centrically above the rigid square footing (Figure 7).

Figure 7. Shaker

Accelerometers are employed to measure signal time histories on the shaker foundation and at several distances from the source along an array. Three accelerometers were deployed through the inverted pyramid and three more were deployed through the linear barrier. The three components of harmonic vibrations (vertical, horizontal longitudinal and transversal to the array) were recorded.

The field shaking was performed before and after the creation of the barriers. The main characteristics of the applied signals are shown in the Table 3.

Table 3. Characteristics of the applied shaking signals.

#	Amplitude (N)	Frequency (Hz)	Δt (s)	Duration (s)
1	188	10.3	0.0005	90
2	348	13.8		
3	710	20.5		

5 EXPERIMENTAL RESULTS

The results of the field tests are analysed in terms of ratio η between the peak values of the acceleration time history with and without the barriers. All the components of the time history accelerations were considered for both the schemes.

5.1 Inverted pyramid barrier

As an example two recorded signals are plotted in Figure 6 and 7. The vertical component of the acceleration time history #1, recorded at sensor n.0 that is located within the isolated ground, is plotted in Figure 9 while in Figure 8 the same component recorded at the same position before the barrier installation is plotted.

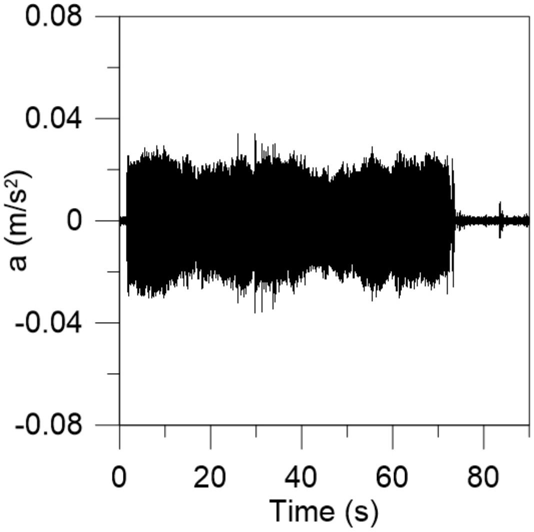


Figure 8. Recorded vertical component of acceleration (signal #1) at distance 8 m from the source without inverted pyramid barrier

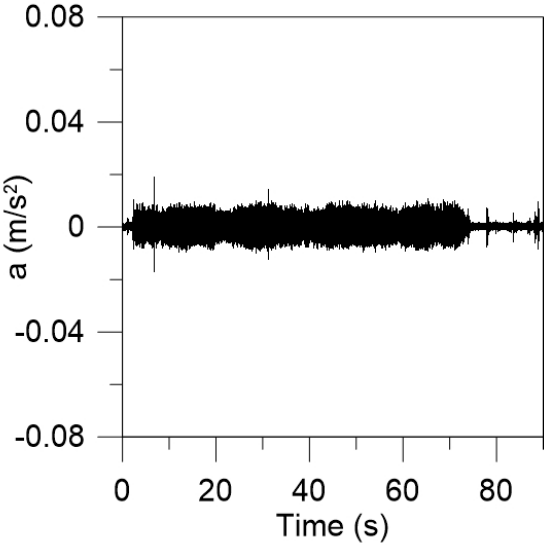


Figure 9. Recorded vertical component of acceleration (signal #1) at distance 8 m from the source with inverted pyramid barrier

The ratio η, between the maximum values of the vertical component of acceleration time history with and without the inverted pyramid barrier, for the signal #1, is plotted in Figure 10, with respect to the distance of the accelerometers from the vibrodyne. This shows the effect of the barrier on the wave propagation at surface.

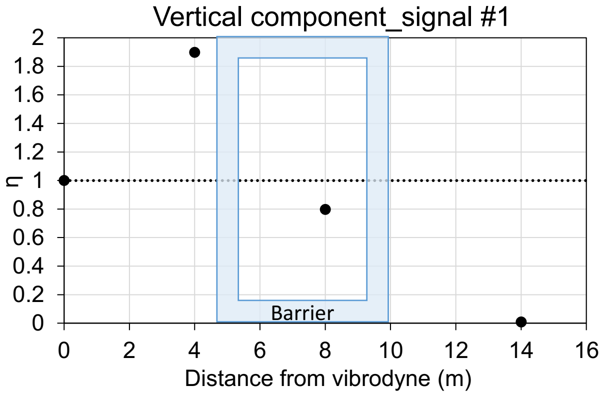


Figure 10. Efficiency ratio η for the vertical component of acceleration (signal #1) with distance from the source (inverted pyramid barrier).

Looking to all the results it can be concluded that for all the components of the acceleration there is an amplification before the barrier and a de-amplification after the barrier. This effect is due to a complex mechanism of wave reflection: the wave pattern becomes irregular due to the geometry of the barrier.

At all considered source frequencies, the barrier causes significantly reduction of the soil vibrations. Inverted pyramid barrier gives the best isolation effect in the frequency of 10.3 Hz for the vertical component. The maximum reduction measured in the experiment was 99 %.

5.2 Trench barrier

Two of the recorded signals are plotted in Figure 11 and 12. The vertical component of the acceleration time history #1, recorded at sensor n. 0 that is located on the vertical barrier, is plotted in Figure 10 while in Figure 9 the same component recorded at the same position before the barrier installation is plotted.

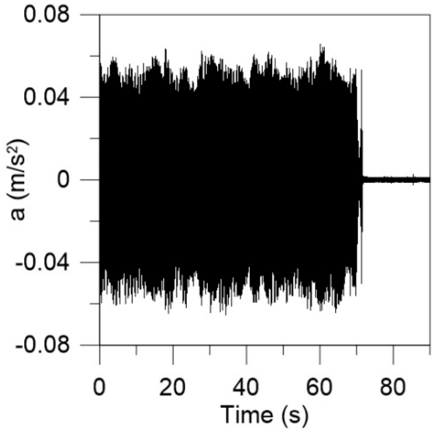


Figure 11. Recorded vertical component of acceleration (signal #1) at distance 5 m from the source without vertical barrier

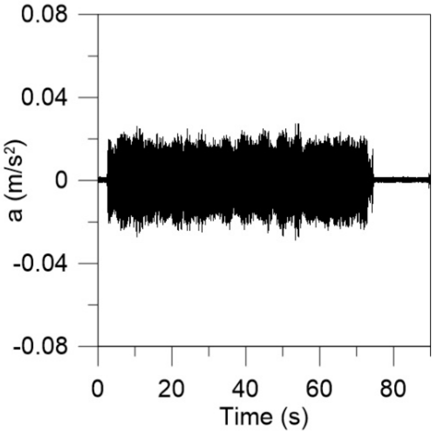


Figure 12. Recorded vertical component of acceleration (signal #1) at distance 5 m from the source with vertical barrier

The ratio η, between the maximum values of the vertical component of acceleration time history with and without the vertical barrier, for the signal #1, is plotted in Figure 13, with respect to the distance of the accelerometers from the vibrodyne. In this case, the effect of wave reflection is more evident, causing an amplification between the barrier and the source.

Considering all the results, the vertical barrier causes significantly reduction of the soil vibrations. The maximum reduction measured in the experiment was 70%.

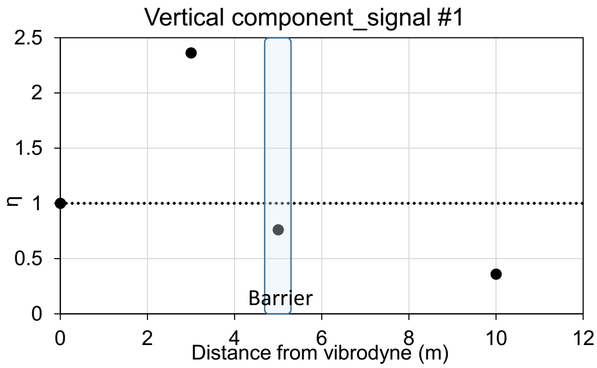


Figure 13. Efficiency ratio η for the vertical component of acceleration (signal #1) with distance from the source (vertical barrier).

6 CONCLUDING REMARKS

The results obtained in an experimental activity and shown in this paper describe the ability of a possible technique to reduce the impact of soil vibrations.

A series of field tests are performed to examine the screening efficiency of barriers filled with a kind of polymer (SAP, Super Absorbing Polymers) characterized by a low shear resistance modulus.

Following the results of preliminary numerical analyses, the barriers were constructed in two different geometrical configurations: an inverted pyramid and a vertical barrier. The shear waves were generated using a vibrant source namely *vibrodyne* characterized by controlled force and frequency.

From field measurements with and without the barrier, the amplitude reduction ratio is estimated at different points of interest.

In-situ measurements confirm that vibration screening systems using this kind of barriers can be applied as a reduction measure for soil vibrations.

7 ACKNOWLEDGEMENTS

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