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DIMENSIONLESS FACTORS GOVERNING THE LATERAL DISCONNECTION EFFECTIVENESS

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Abstract

The lateral disconnection technique consists in removing the soil on the sides of the shallow foundations with considerable embedment. In this way, the foundation-soil contact will be through the foundation base only. The reduction of the translational and rotational soil-foundation stiffness, generated by the lateral disconnection, lengthens the fundamental period of the soil-structure system. Depending on the site-specific hazard, this may result in a significant reduction of the seismic actions on the structure itself. The paper shows the preliminary results of a parametric study aimed at identifying the main dimensionless groups governing the effectiveness of the lateral disconnection intervention in lengthening the fundamental period of the soil-structure system.

Keywords: Geotechnical seismic isolation; Lateral Disconnection; Soil Structure Interaction.

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1 INTRODUCTION

Geotechnical seismic isolation (named GSI) transposes the effects of traditional seismic isolation into the ground. Yegian & Catan (2004) demonstrated numerically and experimentally that the insertion of a sliding surface (*i.e*. a special geotextile), characterized by a low friction angle placed immediately below the foundations, would be able to dissipate the energy of earthquakes. Similarly, Kirtas et al. (2009) studied numerically the effect of creating vertical and horizontal, rigid or soft, barriers in the foundation soil. Brennan (2013) and Nappa (2016) validated the idea of seismically isolating a building by placing soft barriers in the ground through various centrifuge tests. Further aspects of seismic isolation of existing building through soft barriers such as advanced dynamic characterisation of soft mixtures, simplified modelling procedures and numerical analysis results can be found in Somma *et al.* 2023. On the contrary, sand-rubber mixtures (named rubber-soil), which can be placed with relatively easy as foundation soil for a new building, have also been particularly investigated in seismic loads mitigation (Pitilakis, 2015). All the procedures outlined have as a common strategy the increase of the natural period of vibration and/or the damping of the soil-structure system. However, there are still numerous uncertainties and difficulties linked to the technological installation procedures (especially for existing buildings), as well as a certain diffidence in operating only and exclusively through the modification of the foundation soil.

A technologically simple and intuitive way to lengthen the fundamental period of the soil-structure system is the lateral disconnection of the shallow foundations from the adjacent soil. In fact, the creation of a small gap, laterally the foundations side, modifies the horizontal and rotational stiffness of the soil-foundation, thus contributing to increase the fundamental period of the soil-structure system itself (Somma *et al.* 2021b). In some contexts of seismic hazard, and for foundations with a considerable embedment in the soil (*i.e.* masonry buildings), this technique determines a significant reduction of seismic actions and, therefore, an excellent low-cost seismic improvement technique (Somma *et al.* 2021a, Somma *et al.* 2022). However, in other cases, lateral disconnection has been shown to provide little benefit compared to classical structural retrofitting (Somma *et al.* 2023). Using dimensional analysis, this memory identifies, through FEM analysis, the parameters that most influence the period elongation produced by the lateral disconnection in order to determine the circumstances where this intervention could generate significant seismic benefits.

2 NUMERICAL ANALYSIS

The numerical analyses, aimed at identifying the natural period of vibration with soil-structure interaction, are conducted using the software Plaxis 2D (Brinkgreve, 2013). Fig. 1 generically shows the FEM model used.

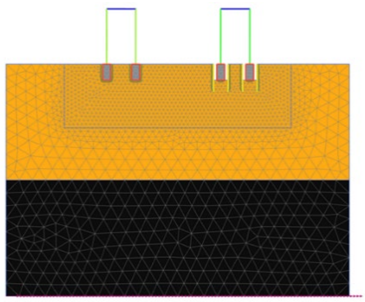

Fig. 1. Finite element model used for the numerical analysis

It is possible to see that the two structural models, with and without lateral disconnection, were studied simultaneously within each analysis. In particular the structure with lateral disconnection will be named *GSI* structure while the one without lateral disconnection *NO GSI* structure. The structural model used is a one-storey, one-bay building with discontinuous shallow foundations. The gap generated by the lateral disconnection technique is supported by the presence of four small rigid cantilever walls, modelled as plate elements, whose only task is to support the lateral load of soil. The relative distance between the two structures and between the structures and the boundaries of the model, ensures that there are no interferences (Jiang & Yan, 1998). The columns and the crossbeams of the structures are modelled as plate elements. In particular, the crossbeams are characterised by a very high normal stiffness, *EA,* and flexural stiffness, *EI,* values, equal to, respectively, 10^8kN/m and 10^9 kNm^2/m (where *E* is the Young modulus, *I* the inertia and A is the area of the plate in plane strain condition). The high flexural and normal stiffness of the crossbeams generates the so called "*Grinter frame*" effect. The flexural stiffness value of the columns is chosen, once the structural mass is selected, to generate the desired structural period in fixed base condition. The soil is modelled as homogeneous visco-elastic material model. Since the depth of the bedrock is one of the parameters influencing the dynamic soil-foundation stiffness coefficients (Gazetas 1991), it was explicitly modelled in the numerical model. The water table is not present.

The numerical procedure to calculate the period elongation, generated by the soil deformability on the two analysed structures, consists of several phases:

1. In a static phase, application of a horizontal force on the roof of the two structures.
2. In a dynamic phase, deactivation of the static force, and computation of the free oscillations decay generated.
3. From the free oscillations, using the Fourier transform, it is possible to know the predominant period of the structure with soil structure interaction and, therefore, to know the period elongation with respect to the fixed base case ($\frac{\tilde{T}}{T_s}$).
4. Finally, it is possible to evaluate the relative period elongation between the two systems, with and without intervention, as: $\Delta = \frac{\tilde{T}_{disc} - \tilde{T}_{conn}}{\tilde{T}_{conn}}$; this value can be understood as an efficiency measure of the lateral disconnection in the elongations of the soil-structure natural period.

As the free decay oscillations are produced by a static force applied within the mesh, it was preferred to use perfectly absorbent viscous contours on lateral boundaries (Lysmer and Kuhlemeyer, 1969).

2.1 Application of dimensional analysis on period elongation

In order to delineate the dimensionless parameters governing the period lengthening produced by lateral disconnection, it is necessary to identify all the independent variables involved, q_i, as well as their physical dimensions.

Table 1. Independent variables involved in the period elongation generated by the soil deformability

Parameters		Description of the variable
Variable	Dimension	
T_s	T	Fixed base period of the structure

H_s	L	Height of mass centroid in the first modal form for the fixed base structure
B	L	Width of single strip foundation
W	L	Base width of the building
D	L	Embedment of the foundation
d	L	Effective soil-foundation contact
m_s	ML^{-1}	Participating mass of the first modal form in plane cond.
v_f	-	Poisson coefficient of foundation material
p_t	ML^{-3}	Mass density of soil
p_f	ML^{-3}	Mass density of foundation
v_t	-	Possion coefficient of soil material
V_t	LT^{-1}	Shear waves velocity in the soil material
V_f	LT^{-1}	Shear waves velocity of the foundation material
H_b	L	Depth of the bedrock

The fundamental period of the structure, considering the soil-structure interaction ($\widetilde{T}$), can therefore be expressed as a function of the identified variables:

$$\widetilde{T} = f(T_s, H_s, B, W, D, d, m_s, v_f, p_t, p_f, v_t, V_t, V_f, H_b) \tag{1}$$

The number of variables identified is 14, while the number of independent units is 3 (mass, time, length). Therefore, it would be possible to identify 14-3=11 dimensionless groups (Buckingham's Theorem). It is possible to identify the following dimensionless groups, using V_t, W, p_t as the dimensionally independent variables (*dimensional base*). It should be remembered that this choice is arbitrary and other bases can be chosen to obtain other significant dimensionless groups. A characteristic value for the resonance period of the structure is obviously given by the fixed base period T_s, so $U = \frac{\widetilde{T}}{T_s}$ is a dimensionless number representing the period elongation compared to the fixed base case. The dimensionless period lengthening, can, therefore, be expressed as a function of the following dimensionless parameters:

$$\frac{\widetilde{T}}{T_s} = f\left(\frac{T_s V_t}{W}, \frac{H_s}{W}, \frac{B}{W}, \frac{D}{W}, \frac{d}{W}, \frac{m_s}{p_t W^2}, \frac{p_f}{p_t}, v_f, v_t, \frac{V_f}{V_t}, \frac{H_b}{W}\right) \tag{2}$$

$$U = F(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6, \Pi_7, \Pi_8, \Pi_9, \Pi_{10}, \Pi_{11}) \tag{3}$$

It is possible to manipulate these dimensionless groups, obtaining other dimensionless groups produced from the originals (for example, $\Pi_1' = \frac{\Pi_2}{\Pi_1} = \frac{H_s}{V_s T_s}$). The following dimensionless groups can be found:

$$\frac{\widetilde{T}}{T_s} = f\left(\frac{H_s}{V_t T_s}, \frac{H_s}{W}, \frac{B}{W}, \frac{D}{B}, \frac{d}{D}, \frac{m_s}{p_t W H_s}, \frac{p_f}{p_t}, v_f, v_t, \frac{V_f}{V_t}, \frac{H_b}{B}\right) \quad (4)$$

The dimensionless period lengthening is therefore a function of 11 dimensionless parameters. It is obvious that an engineering problem governed by 11 dimensionless parameters is unmanageable and, for this reason, some of them will be neglected in the following sensitivity analysis. For example, it is possible to neglect small variations in the Poisson's modulus for the soil considered (~ 0.2-0.3) and for the concrete material of the foundation (~ 0.2). Assuming infinitely stiff foundations, it is possible to neglect the parameter Π_{10} since it is much higher than unity in every possible scenario. It is possible to neglect the parameter Π_{11} because, except for particular cases of outcropping bedrock, this ratio is always higher than 10, as well as it is possible to neglect the variations of the parameter Π_7 because it rarely assumes values that are significantly different from unity. It is also possible to note that some of these parameters (*i.e.* Π_1, Π_6) coincide with those found by Veletsos (1974) and Bielak (1975) (respectively, structure to soil relative stiffness and structure to soil relative mass ratio).

2.2. Illustrative example and demonstration of physical similarity

In order to demonstrate the effectiveness of the dimensionless groups found, it is possible to carry out parametrically similar numerical analyses. In particular, the following vector of dimensionless parameters has been fixed:

$$\pi = (0.15, 0.85, 0.15, 1, 1, 0.24, 1.10, 0.2, 0.25, 20, 20) \quad (5)$$

Eight different numerical models with the same dimensionless parameters were therefore produced (Table 2).

Table 2. Numerical models created with identical dimensionless parameters but different physical dimensions.

Variables		Numerical models produced							
Name	Unit	I	II	III	IV	V	VI	VII	VIII
T_b	[s]	0.3	0.5	0.8	0.8	0.3	0.5	0.3	0.8
H_s	[m]	5.5	5.5	5.5	11	8.25	13.75	13.75	13.75
B	[m]	1	1	1	2	1.5	2.5	2.5	2.5
W	[m]	6.5	6.5	6.5	13	9.75	16.25	16.25	16.25
D	[m]	1	1	1	2	1.5	2.5	2.5	2.5
d	[m]	1	1	1	2	1.5	2.5	2.5	2.5
m_s	[Kg]	16819	33639	61671	123343	25229	84097	42048	154179
v_f	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
p_t	[Kg/m^3]	1911	3822	7008	3504	1274	1529	764	2803
p_f	[Kg/m^3]	2102	4204	7708	3854	1401	1681	840	3083
v_t	-	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

V_t	[m/s]	122	73	44	91	183	183	305	114
V_f	[m/s]	2444	1466	916	1401	3666	3666	6111	2291
H_b	[m]	20	20	20	40	30	50	50	50

By applying the procedure described in Section 2, Figure 2 shows the period lengthening related to the fixed base. Since the period elongation with respect to the fixed base case are practically constant in the 8 analyses conducted, it is possible to state that also the period variations between *GSI* and *NO GSI* structure (called Δ, see section 2) is constant too. It is possible to conclude that the selected dimensionless parameters control the physical process analysed. It is important to underline that small discrepancies may be due to numerical aspects such as the axial stiffness of the columns which has not been included in the dimensionless parameters space.

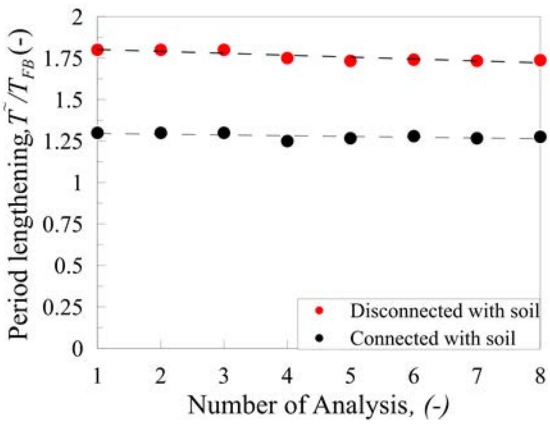

Fig. 2. Similar period lengthening, in different numerical analysis, using the same a-dimensional group

2.3. Sensitivity analysis

The previous paragraph has shown that the period variations between the two structures, with and without lateral disconnection, are the same as long as the dimensionless parameters are constant, confirming that the Buckingham's Theorem was correctly applied. In order to identify the most significant dimensionless parameters, it is possible to vary each dimensionless parameter individually, leaving the value of the others fixed (Fig. 3). In particular, each individual dimensionless parameter was varied up to a maximum of a 100%, increasing or decreasing, their initial value (see equation 5 for the initial values). The graphs show the period variations between *NO GSI* and *GSI* structure (called Δ) for two different types of lateral disconnection interventions. Indeed, in *"both sides"* case, the disconnection occurs on both sides of the foundations (*i.e.* inside and outside the structure itself, on the left and on the right of each strip foundation). In the *"externally only"* case, on the other hand, the disconnection was generated only on the external side of the structure leaving the ground between the two adjacent foundations untouched. This solution has been introduced because it obviously represents a considerable technological simplification.

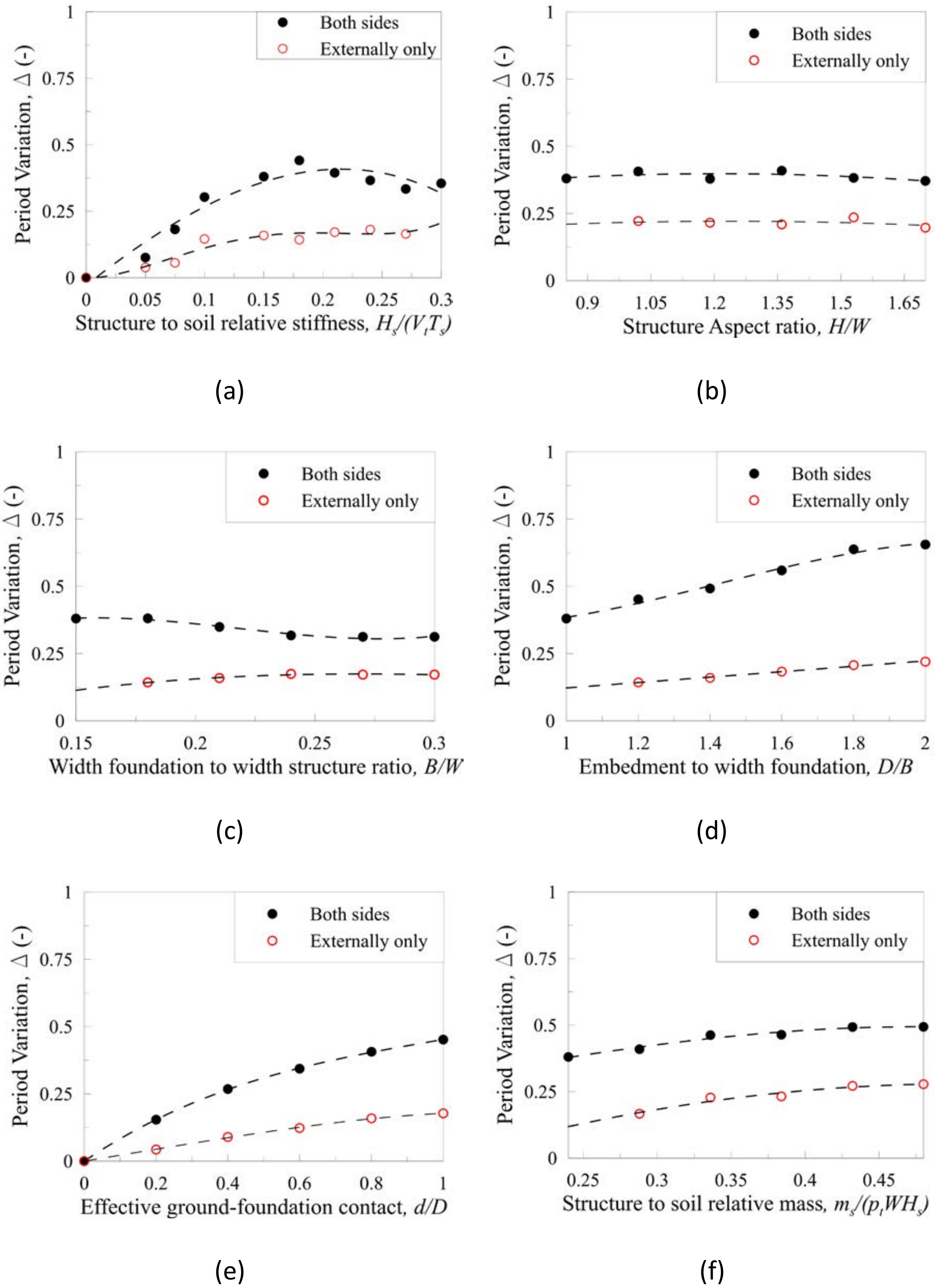

Fig. 3. Sensitivity analysis obtained by increasing or decreasing the dimensionless parameters up to a maximum of 100% of their initial value; (a) structure to soil stiffness ratio, (b) structure aspect ratio (c) width foundation to width structure ratio (d) Embedment to width foundation (e) Effective ground-foundation contact (f) Structure to soil relative mass

The graphs show that the *"externally only"* lateral disconnection solution, although easier to apply technologically, is less efficient than the *"both sides"* case. For all dimensionless parameters, it is possible to state that the efficiency, Δ, is almost halved in the *"externally only"* solution.

Some dimensionless parameters seem to have a relatively small influence on the period variations between the connected and disconnected structure. In particular, for the parameters Π_2, Π_3 the period variation trend seems to be almost independent from the variation of the dimensionless parameter considered (*i.e.* horizontal tangent). As far as the parameter Π_6 is concerned, *i.e.* the ratio between the mass of the structure and the mass of participating soil involved, a slight increase in the period variation can be observed as this parameter increases. This could indicate a greater efficiency of the technique for particularly massive structures related to the participating mass of soil.

The modification of the relative structure to soil stiffness (Fig. 3a), in the engineering-significant range of 0.05-0.2 (NIST, 2012), seems to significantly influence the period elongation between the two structures. In particular, the more rigid the structure with respect to the soil, the more effective the disconnection. This is an interesting result since it is possible to understand that the applicability of this intervention, in contexts where the foundation soil is particularly rigid with respect to the structure, may be useless. This happens because the high stiffness of the soil below the foundations inhibits the global rotations of the structure more significantly than the lateral soil. For this reason, the two structures tend to have approximately the same period with and without intervention. Lateral disconnection, therefore, may give greater benefits, in terms of period extension, for rigid structures on deformable soils.

A further significant dimensionless parameter is the *D/B* ratio of the foundations. It is clear that this parameter affects a lot the effectiveness of lateral disconnection. Very high values of this ratio indicate foundations with considerable embedment for which the removal of adjacent soil can have a significant effect. For values less than unity the relative period elongations are reduced and the lateral disconnection technique loses its effectiveness.

The effective lateral contact of the soil with respect to the total embedment (*d/D*) of the foundation is also particularly important. In fact, if for the *NO GSI* structure the effective contact is particularly low, the relative period variations, Δ, is reduced. In case of *d/D*=0, indeed, there is zero lateral effective contact between the foundation and the ground and no period variations, Δ, will be generated by the lateral disconnection. In general, the effective contact is never equal to unity (perfect contact *d/D*=1) but tends to be reduced by soil non linearities such as gapping (Gazetas, 1991).

3 CONCLUSIONS

The memory summarised the results of a preliminar parametric study conducted using significant dimensionless groups. The purpose of the parametric study was to understand the importance of some dimensionless groups on the effectiveness of the lateral disconnection technique. The increase of the relative structure-to-soil stiffness as well as, to a lesser extent, the relative structure-to-soil mass ratio positively influence the effectiveness of the lateral disconnection technique. The *D/B* ratio plays a fundamental role in the effectiveness of this technique. Especially for existing masonry buildings, for which traditional construction technique included to thicken the load-bearing masonry walls and to sink it several metres into the ground, this ratio can be considerably high and lateral disconnection can represent an economic and alternative seismic improvement technique.

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