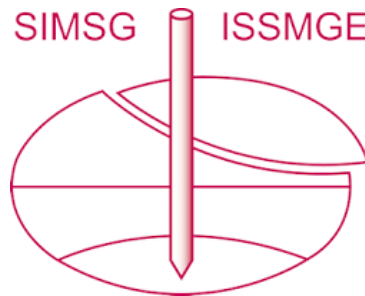


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Effects of lateral disconnections on the seismic response of shallow foundations

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ABSTRACT: The paper examines the effects of removing the lateral ground connection between embedded foundations and surrounding soil on the dynamic soil-structure interaction. The lateral disconnection produces (i) a reduction in the overall stiffness leading to a decrease in the seismic actions; (ii) a shrinkage of the interaction domain of the foundation. In order to take into account both these factors the method introduced by Wolf was used to assess the actions at the structure level; the reduction in the bearing capacity due to the disconnection was estimated by suitably employing the limit analysis; finally, both the pseudo-static and the push-over methods of analysis were adopted. The proposed procedure was applied to a one-story building and a parametric analysis was carried out varying both the dimensions of the lateral disconnection and the stiffness of the foundation soil. In order to show the effectiveness of the proposed intervention, the obtained results are presented for two selected cases.

1 INTRODUCTION

Despite of the recent advances in earthquake engineering technology, a large number of existing masonry structures and historical buildings (widespread in zones that have been recently identified as seismic) are not safe under seismic conditions. In fact, the structural damages reported during the last earthquakes in Central (2016-2017) and Northern Italy (2012) provide a clear evidence.

A proper seismic resistant design should ensure negligible or no damages regardless the magnitude and the epicenter location of earthquakes. Since the 1960s, the minimization of damages has been achieved by employing both Structural and Geotechnical Seismic Isolation (SSI and GSI) systems. Yet, the implementation and maintenance of conventional SSI systems can be quite expensive. As a consequence, these systems are adopted only for important structures.

While the widespread SSI systems (Skinner et al., 1993; Naeim & Kelly, 1999; Kelly, 1997) use either the sliding or flexible interfaces between the structure and its foundation, the GSI systems directly employ natural earth materials and/or man-made reinforced earth materials (Tsang et al., 2012) for seismic mitigation.

Historically, the concept of vibration screening was initially proposed by Woods (1968) and then developed by achieving interception, scattering, and diffraction of surface waves using barriers such as trenches (Beskos et al., 1986), sheet-pile walls (Andersen & Liinggaard 2005),

and piles (Liao & Sangrey, 1978). Waves barriers have been successfully employed to mitigate ground vibrations from railways and machine foundations. More recently, several Authors (Kirtas et al, 2009a & 2009b; Lombardi et al, 2014; Flora et al, 2018) proposed to adopt sub-soil interventions as seismic isolators.

This paper focuses on the effects of a laterally disconnecting embedded foundations from the lateral soil on the seismic response of existing buildings. The excavation of a trench around an existing foundation proposed herein does not constitute a wave barrier but aims at increasing the natural period of the soil-foundation-structure system. As a matter of fact, numerical models including soil, foundation and structure are generally characterized by longer natural periods of vibration with respect to those with fixed-base and the lateral disconnection leads to a further increase in periods.

The idea of physical disconnection of the foundation allows combining both the reduction in horizontal loads acting on the superstructure under seismic conditions and the simplicity of application for existing structures. However, the removal of the ground adjacent to the foundation causes a reduction in the bearing capacity of the soil-foundation system and an associated increase in rotation under horizontal loads. Therefore, the net effect of disconnecting the foundation should be such as to guarantee seismic safety conditions of the structure and its post-seismic functionality, in order for the disconnection to be a successful isolation system.

2 THEORETICAL MODEL

2.1 Position of the problem

With the aim of studying the effectiveness of the lateral disconnection represented in Figure 1.b, a theoretical procedure has been proposed considering (i) the evaluation of an equivalent stiffness for the soil-structure system to take into account the reduction in the stiffness of the overall soil-foundation-structure system induced by the disconnection; (ii) the soil-foundation interaction domains to quantify the reduction in bearing capacity due to the removal of the lateral soil; (iii) the push-over curve of the foundation to calculate the change in base rotation.

For the sake of simplicity, the dynamic problem is solved by substructuring the system. Such a simplified procedure, largely employed in the common practice, allows to obtain an approximate solution capable to correctly describe the seismic behaviour of the system. Thus, the effect of the superstructure on the foundation is reduced to equivalent generalized forces. In case of 2D problems, the superstructure will transmit N , H and M , denoting vertical and horizontal forces and moment acting on a strip footing of width B and placed at a depth D from the ground surface (Figure 1.a).

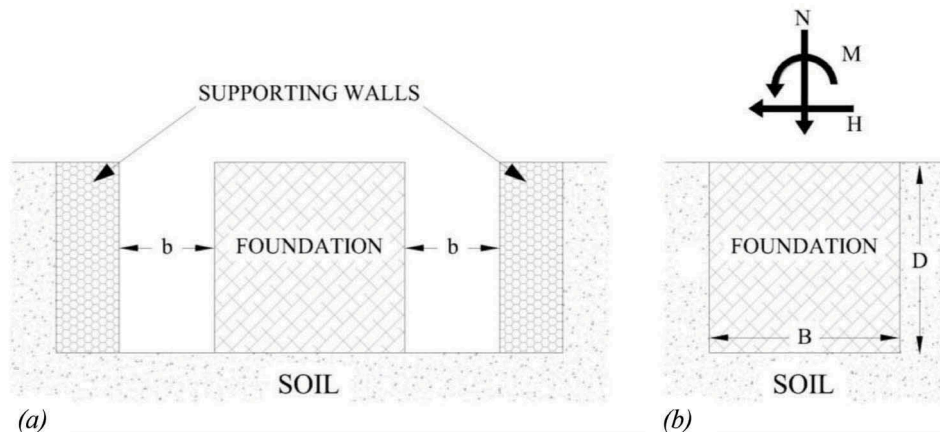


Figure 1. a) Disconnected foundation; b) Connected foundation and acting forces

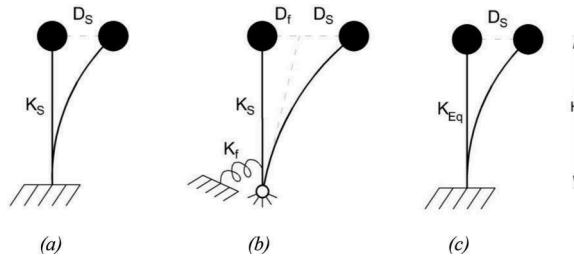


Figure 2. a) structure perfectly fixed to the base; b) structure free to rotate at the base; c) structure with equivalent stiffness perfectly fixed to the base (Wolf, 1985).

2.2 Reduction in the overall stiffness

First of all, the lack of lateral soil leads to an intuitive reduction in the foundation- soil stiffness (K_f). In fact, without any soil removal, the system can be considered either rigidly-supported (Figure 2.a) or flexibly-supported with a stiffness of the base constraint K_f (Figure 2.b). After the lateral disconnection has been introduced, K_f reduces.

According to Wolf (1985) if K_f denotes the stiffness of the soil-foundation system referring only to the rotational mode, an equivalent fixed-base system of stiffness K_{eq} can be introduced (Figure 2.c), as:

$$K_{eq} = \frac{K_S D_S}{D_S + D_f} = \frac{K_S}{1 + H^2 \cdot K_S / K_f}, \quad (1)$$

in which K_S and K_f are the stiffnesses of the structure and the foundation respectively; D_S stands for the structural horizontal displacement; D_f for the lateral displacement due to the rotational capability of the foundation and H for the height of the equivalent SDOF (Figure 2.c).

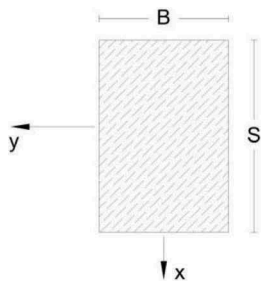
The procedure to evaluate the stiffness of the structural elements K_S is well established. Owing to the non-linear behaviour of the foundation soil when subject to dynamic loads, the stiffness K_f will depend on: (i) the nature and the deformability of the supporting soil and (ii) the geometry and the inertia of the foundation. To take into account all these factors the solution proposed by Gazetas (1991) for the rocking mode were adopted herein (Figure 3).

In Figure 3 the soil-foundation stiffness for surface foundations is denoted as $K_{f,sur}$, whereas $K_{f,emb} = \mu_{r0x} \cdot K_{f,sur}$ is the stiffness of embedded foundations. Herein, the embedded case is assumed as the foundation connected to the lateral soil ($K_{f,emb} = K_{f,conn}$). Similarly, the case of foundation resting on the ground surface is considered as the disconnected case ($K_{f,sur} = K_{f,disc}$). In the solution proposed by Gazetas the soil-foundation stiffness depends on (i) shear modulus G and Poisson ratio ν of foundation soil; (ii) area moment of inertia I_{bx} of the foundation-soil contact area around x -axis (Figure 3); (iii) shape (S/B) and depth (D/B) ratios that directly influence the stiffness ratio μ_{r0x} . Since $\mu_{r0x} > 1$, using $K_{f,sur}$ instead of $K_{f,emb}$ implies an increase in the natural period of the equivalent system.

Depending on the initial value of the system period and on the shape of the design spectrum, the introduction of the disconnection and the consequent increase in period might lead to a reduction in the seismic input. In fact, because of the shape of the spectrum, the disconnection may not be associated with the same advantageous effect in all cases. Thus, an increase in the period could lead, in some cases, also to an increase in the seismic input.

By using Wolf's model and Gazetas' formulas, it is possible to evaluate the increase in the natural period, normalized with respect to the natural period of the system with an embedded foundation:

$$\Delta T^* = \frac{\Delta T}{T} = \sqrt{\mu_{r0x} \frac{(\lambda+1)}{\mu_{r0x} \cdot \lambda + 1}} - 1, \quad (2)$$



$$K_{f,sur} = \frac{G}{1-\nu} I_{bx}^{0.75} \left(\frac{S}{B}\right)^{0.25} \left(2.4 + 0.5 \frac{B}{S}\right)$$

$$K_{f,emb} = K_{f,sur} \cdot \mu_{r0x} = K_{f,sur} \cdot \left\{ 1 + 1.26 \cdot \frac{2D}{B} \left[1 + \frac{2D}{B} \sqrt{\frac{B}{S}} \right] \right\}$$

I_{bx} area moment of inertia of the foundation-soil contact surface around the x axis

Figure 3. Gazetas' formulas (1991) applied to foundations with perfect contact between sidewall and soil

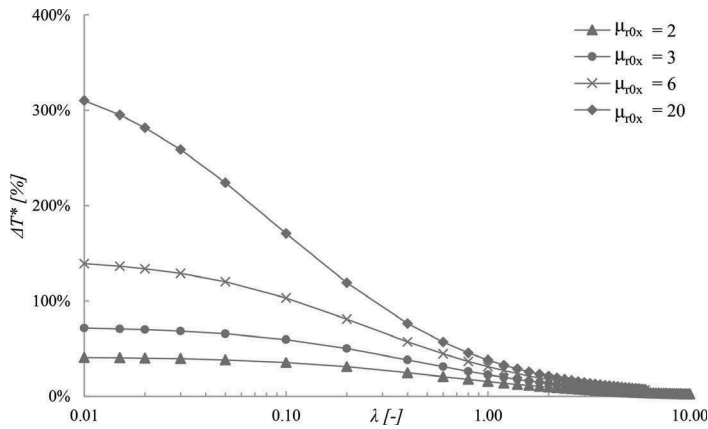


Figure 4. Increase in natural period by varying the interaction ratio (fixed μ_{r0x})

where $\lambda = K_{f,sur}/(H^2 K_S)$ is the interaction ratio. The dependence of ΔT^* on λ for different stiffness ratios is plotted in Figure 4. The range of variation of μ_{r0x} were evaluated by considering $S/B = 1 \div 10$ and $D/B = 0, 1 \div 3$.

2.3 Reduction in bearing capacity

The trinomial formula by Brinch-Hansen (1961) is commonly employed to evaluate the bearing capacity of shallow foundations. The proposed removal of a slice of soil adjacent to the foundation leads to a reduction of the lateral load \bar{q} assumed to be applied aside the foundation in the considered failure mechanism (Figure 5).

In order to quantify the reduction in bearing capacity associated with the removal of part of the lateral load, the kinematic theorem of limit analysis was applied to a cohesionless soil. The stabilizing term due to the lateral load will be reduced by a reduction factor F defined as:

$$F = \frac{L - b}{L}, \tag{3}$$

where L is the width of the failure mechanism before disconnection. It is evident from Equation 3 that too large a value of b may cause an unacceptable reduction in the bearing capacity of the foundation. The designer is expected to properly modify F to optimize the intervention.

The well-known relationship between the lateral load and the stresses acting on the foundation (defined as in Figure 1.a) allows evaluating the interaction domains $H-N$, $M-N$ and $H-M$ for connected foundations by varying, respectively, (i) the inclination i , (ii) the eccentricity e

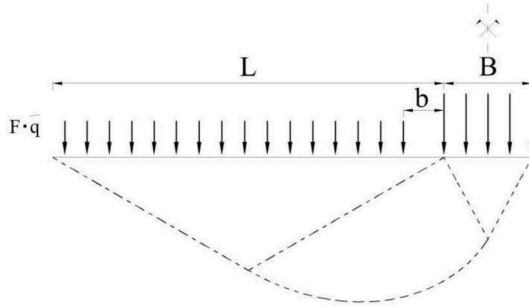


Figure 5. Effect of removal of lateral load (\bar{q}) on the failure mechanism through the reduction factor (F)

of the external vertical load and (iii) the i/e ratio. Thus, by using the reduction factor F the interaction curves for the disconnected case can be also obtained.

To calculate the failure mechanism width (L) for various inclinations (i), the method of characteristic lines has been directly used. To consider also the effect of variation of the eccentricity e on the evaluation of L , the proportionality between the mechanism shape for fixed inclination and eccentricity suggested by De Simone & Restaino (1985) is used.

2.4 Increase in base rotation

In order to determine the increase in structural horizontal displacements, a push-over analysis has been performed to evaluate the rotation at the foundation level under seismic conditions after the disconnection.

A simplified procedure to define the push-over curve of the foundation is here proposed by using the Butterfield's law (1980) reinterpreted in terms of overturning moment M and rotation ϑ :

$$M/M_{LIM} = 1 - \exp(-K_f \cdot \vartheta/M_{LIM}). \quad (4)$$

The shape of this curve is directly related to the stiffness K_f of the soil-foundation system (Figure 3) and to the limit bending moment, M_{LIM} . The latter has been evaluated by means of Figure 6, where the interaction domain is drawn and the ratio $i/e = H/M$ is fixed for the current acting forces coming from the superstructure (Figure 1).

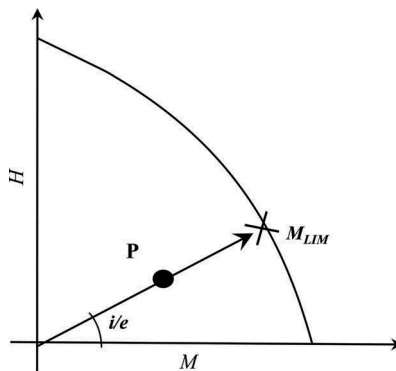


Figure 6. Limit value of the bending moment evaluated on the interaction curve for a fixed ratio of load inclination and eccentricity (i/e)

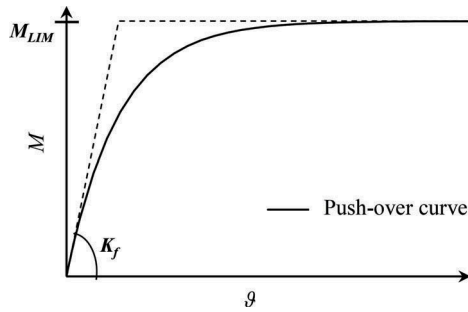


Figure 7. Push-over curve obtained by means of Butterfield’s interpolation.

Thus, once the actions transmitted by the superstructure to the foundation (especially the moment M) are known, the corresponding rotation ϑ can be evaluated by means of the push over curve (Figure 7).

3 APPLICATIONS

In order to verify the effectiveness of the intervention, the proposed procedure has been applied to the case of a single-story building based on isolated plinths, however the procedure can be extended also to multi-story buildings by determining equivalent SDOF structures as in Wolf (1985).

By fixing the geometry of the system, i.e. by setting μ_{r0x} ($D/B = 1$, $S/B = 1$, $B = 1$), the soil parameters (Table 1) and the design spectrum (Table 2), two different cases A and B were studied by choosing different values of both shear modulus G and disconnection width b (Table 3).

The initial natural period of the connected system is denoted as T_{conn} (Table 3). This value is obtained by using as foundation stiffness in Equation 1 the connected stiffness by Gazetas ($K_{f,emb} = K_{f,conn}$) (Figure 8).

To evaluate the interaction curves, the Brinch-Hansen’s formula has been used by considering the shape and the depth factors proposed by the same author. To take into account the seismic condition, the seismic bearing capacity factors proposed by Cascone & Casablanca (2016) have been employed.

Table 1. Soil parameters and plinth geometry

c' [kPa]	φ' [°]	ν [-]	γ [kN/m ³]	μ_{r0x} [-]
0	30	0.3	18	8.6

Table 2. Design spectrum parameters (NTC18)

a_g [g]	F_0	T_c^* [s]	q
0.215	2.482	0.341	4.0

Table 3. Shear modulus, Interaction Ratio and ratio between the width of the disconnection and of the foundation

Case of study	G [MPa]	λ [-]	b/B [-]	T_{conn} [s]
A	192	1.52	0.5	0.21
B	11.5	0.1	0.3	0.31

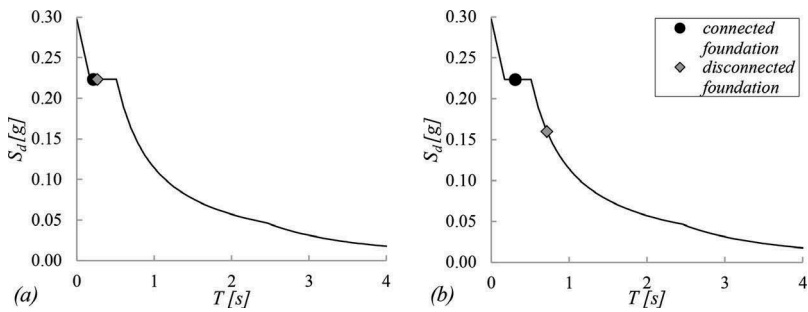


Figure 8. Design spectrum and seismic actions related to connected and disconnected foundation for: a) case A and b) case B.

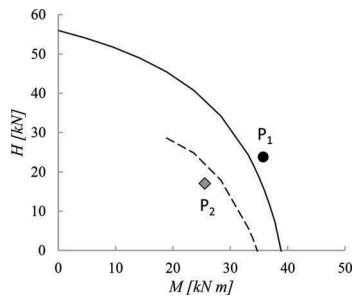


Figure 9. Case B: interaction domain M-H and current actions on connected (solid line and point P_1) and disconnected (dashed line and point P_2) foundations

Figure 8 shows the effect of disconnection on the input acceleration. For *case A* (Figure 8.a) the high value of λ induces a small variation in the period (Equation 2). Furthermore, since the point corresponding to the connected system is located on the plateau of the design spectrum, a null variation in the seismic input is obtained. In *case B* a more significant change in the natural period causes a relevant reduction in the input acceleration (Figure 8.b). This induces a severe reduction in both the horizontal force and bending moment acting on the foundation (points P_1 and P_2 in Figure 9). Disconnection causes also a change in the interaction domain (dashed-line in Figure 9).

The reduction in the size of the interaction domain and the decrease in the seismic actions justifies only in case B the proposed strategy.

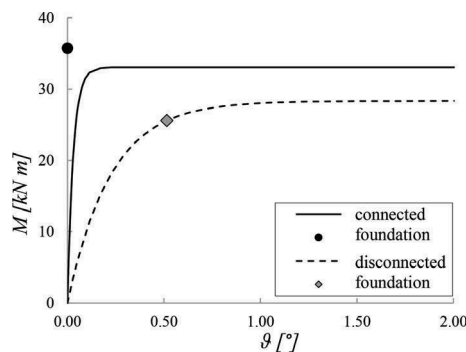


Figure 10. Case B: push over curves and acting moment in case of connected foundation (solid line and black circle) and disconnected foundation (dotted line and grey rhombus).

A confirmation of what already observed in Figure 9 is given by the push-over method (Figure 10). Without disconnection moment applied to the foundation is larger than the maximum overturning moment sustainable by the foundation. In this case the push-over method would give an infinite rotation. In contrast, by using the same method in case of a disconnected system, the push-over method gives a rotation of 0.5° .

4 CONCLUSIONS

A procedure to evaluate the effects induced by the realization of a lateral disconnection on shallow foundations under seismic conditions has been described. The results put in evidence that the effectiveness of this intervention is closely related to (i) the initial period of the overall system and shape of the design spectrum; (ii) the interaction ratio λ directly related through K_f and K_s to the geometry and to both the soil and the structural properties; (iii) the size of the disconnection width b .

The use of the proposed intervention can provide an alternative way of taking advantage of both the non-linear behaviour of the soil and the increase in the period of the soil-foundation-structure system.

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