DYNAMIC RESPONSE OF SOFT SOIL DEPOSITS IMPROVED WITH RIGID INCLUSIONS

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ABSTRACT :

The present paper describes a numerical model to study the seismic response of a soft or loose soil deposit stiffened with rigid inclusions as an alternative foundation solution. Modelling was performed using a 2D dynamic finite element method in which the relevant construction stages of the rigid inclusions and different types of arrays were studied. According to the numerical results, the main effects of rigid inclusions on the response of soft deposits are small changes in spectral ordinates. These changes are more significant for decreasing inclusion spacing at soil periods larger than 1.5s, or increasing spacing at periods less than 1.5s. These effects are more apparent at the perimeter of the stiffened zone than at its core. Support conditions at the tips and heads of the inclusions have a major effect on the dynamic response. Spectral ordinates increased most notably in the short period range when the inclusion tips were socketed in the lower stiff material, being only the second vibration mode affected.

KEYWORDS: Rigid inclusion, dynamic soil response, foundation, finite element method

1. INTRODUCTION

A novel strategy to solve a foundation in a very soft clay deposit in Mexico City or in a loose sand deposit in coastal areas of the country is to improve the mechanical characteristics of the soil, mainly deformability and shear resistance, using rigid inclusions. The main difference between piles and rigid inclusions is that these are not connected to the raft foundation, so there is no need to raft reinforcement at connections, which would reduce the foundation cost. This economic advantage has only recently begun to be fully realized and, consequently rigid inclusions are now becoming increasingly attractive. They may be manufactured with either metal, wood or concrete and their cross section may be cylindrical, tubular or adopt other shapes. Rigid inclusions have been usually employed for: a) Reducing surface settlements generated by building's dead weight loading or by soil mass undergoing active consolidation processes; b) increasing subsoil's overall shearing strength to avoid bottom failures in deep excavations, increasing bearing capacity of the treated soil mass, etc. or any combination of these.

Studies of real case histories and theoretical investigations on the changes of deformability and strength of soil masses improved with rigid inclusions have provided the basics for understanding their overall behavior, leading therefore to the ability to solve subsequent cases (LCPC, 2004; Santoyo *et al*, 2005; SMMS, 2001; SMMS, 2002). Nevertheless, the influence and effects of rigid inclusions on the seismic response of soil masses have not been yet comprehensively studied (*e.g.* Katzenbach & Ittershagen, 2004, Rangel et al, 2006, and Mayoral and Romo, 2006). These effects are analyzed in this paper for the special case of soil deposits that amplify seismic movements, as many areas in the former lake bed in Mexico City. The analysis is carried out using a 2D dynamic finite element method (DFEM), for which typical stratigraphical conditions of Mexico City were considered.

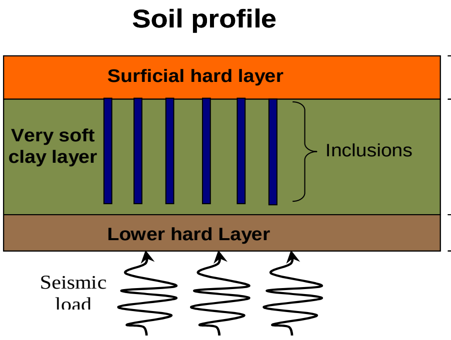
2. CONDITION OF ANALYSIS

Left side of Fig 1 illustrates a way in which rigid inclusions can be used to reduce compressibility of the soft clay layers of a typical lake deposit in Mexico City; the inclusion heads are socketed into a hard superficial crust while tips do not reach the underlying hard layer. Undrained strength (c_{uu}), friction angle and elastic modulus indicated in Fig 1 refer to short term conditions. It is worth noting the extremely high values of plasticity index and water content, which are characteristic of the soft lacustrine Mexico City clays.

The soil-inclusion system analyzed herein starts from initial geostatic stresses existing at the site before installing the inclusions, being afterwards subjected to seismic motion applied at the base of the soil strata.

3. MODELING

The soil-inclusion model under dynamic loading involves three aspects: a) characterization of the soil strata, b) definition of the dynamic excitation at the base of the model and c) determination of the numerical model by means of a finite element mesh with adequate geometry and boundary conditions.



Thickness (m)	Cohesion (KN/m²)	Friction angle (°)	Elastic modulus (kN/m²)	Plasticity index (%)
1 to 7	30 to150	20 to 40	> 8000	40 to 70
20 to 40	10 to 80	nil	1500 to 9000	100 to 400
1 to 4	20 to 130	24 to 32	> 10000	< 40

Figure 1. Subsoil deposit condition overview and inclusion type solution

3.1. Soil Deposit Characterization

The DFEM considers two types of stress-strain relationships for the soil strata, depending on the loading conditions imposed on them. The first loading condition is intended to evaluate geostatic stresses assuming K_o conditions; the second one simulates the installation of the rigid inclusions. Static conditions are assumed for both of them, being the soil modelled as an elastic-plastic solid that follows a Mohr-Coulomb yield criterion. Finally, soil is assumed to be linearly elastic during the application of the undrained seismic loading, using Rayleigh damping as an approximate means of representing the soil and the inclusion's geometrical damping (Hughes, 1987 and Zienkiewicz and Taylor, 1991).

Other material properties that are necessary for the dynamic analyses are density, ρ, Poisson's ratio, ν, undrained shear strength (cohesion, c_u, and friction angle, ϕ), shear and compressive wave velocities, V_s and V_p, elastic deformation modulus E, and bulk modulus, E_{oed}. Additionally, it was necessary to verify the following relationships:

$$V_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \qquad \text{and} \qquad V_p = \sqrt{\frac{(1-\nu)E}{(1+\nu)(1-2\nu)\rho}}$$

Rayleigh damping in a soil is proportional to the mass and stiffness of the system: $C = \alpha M + \beta K$, where C, M, and K respectively represent the mass, damping and stiffness matrices; α and β are the Rayleigh coefficients, which can be determined from the damping ratio ξ_i and corresponding frequency of vibrations ω_i for the first and second modes The relationship between α, β and ξ_i is $\alpha + \beta\,\omega_i^2 = 2\,\omega_i\,\xi_i$.

3.2. Characterization of the Incident Signal

Dynamic analyses were performed assuming that the base of the soil deposit is shaken by the horizontal component of an earthquake acceleration record and that the incoming seismic waves propagate vertically upwards through the deposit. The incident motions were acceleration records (north-south component) measured during the Great Michoacan Earthquake of September 19, 1985, at a rock outcrop (CUMV-UNAM site, Fig 2), which was then transported to the base of the soil deposit (modified bedrock motion), without free field effects.

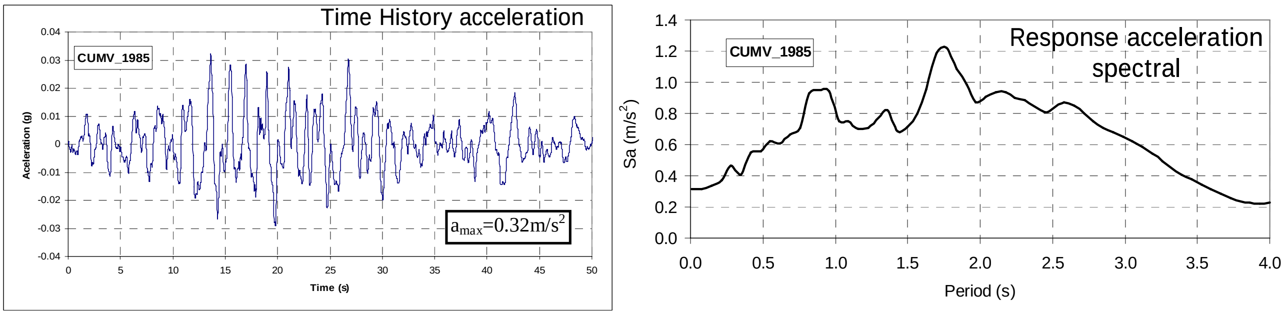


Figure 2. Rock outcropping motion (CUMV, North-South component)

3.3. Numerical Modeling of the Soil Deposit

The initial stress state in the soil deposit is given by geostatic stresses which were estimated assuming that K_o is given by: $K_o = \frac{\nu}{1-\nu}$ or $K_o = 1 - \sin\phi'$. Subsequently, construction of inclusions induces additional changes in the stress state, mainly in the lower part of the clay deposit and in regions close to the inclusions. Both changes were evaluated during the FEM analyses in a sequential way before application of seismic load.

3.3.1. Finite Element Mesh

A bi-dimensional mesh formed by triangular elements with 15-nodes and 4th order interpolation was used for modeling soil strata. Linear beam elements are used to model inclusions. The resulting mesh, shown in Fig. 3, is non-structured with a higher element density in the zone with inclusions. There are two main strata: the upper one is the natural desiccated crust, which in this case acts as a spreading layer, and the lower stratum is formed by soft, deformable clays. Inclusions are placed in the soft clays over an area that depends on the characteristics of the superstructure.

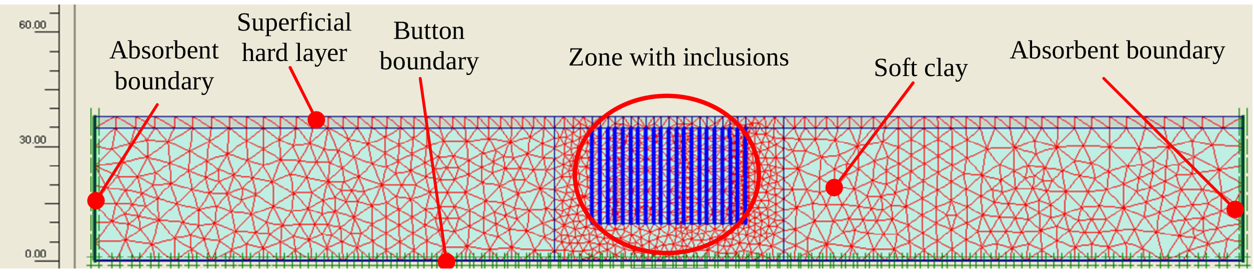


Figure 3. Characterization of the 2D-FE Mesh employed

Movement restrictions at the mesh boundaries are:

Bottom boundary. Vertical displacements are not allowed. Seismic movements (acceleration records) are applied along this boundary.

Upper boundary. It is a free boundary where both, vertical and horizontal displacements are allowed.

Lateral boundary. Horizontal displacements are fixed when modeling the placement of the inclusions. Silent or absorbent boundaries are prescribed during seismic loads, to avoid wave reflections that can induce errors in the computations (Lysmer and Kuhlmeye, 1969). In general the lateral boundaries require being as far as possible from the zone with inclusions, to avoid boundary interference effects. Stress conditions along this boundary must comply with: $\sigma_n = -c_1 \rho V_p \dot{u}_x$ and $\tau = -c_2 \rho V_s \dot{u}_y$, where c_1 and c_2 are relaxation coefficients to improve energy absorption at the boundary.

3.4. Rigid Inclusion Model

An equivalent plane element group is used to represent a group of inclusions in a plane strain scheme. The equivalent element is obtained for the flexural rigidity, *EI*, and normal stiffness, *EA*:

$$(EI)_{equivalent} = (EI)_{soil} + (EI)_{inclusion} \quad \text{and} \quad (EA)_{equivalent} = (EA)_{soil} + (EA)_{inclusion}$$

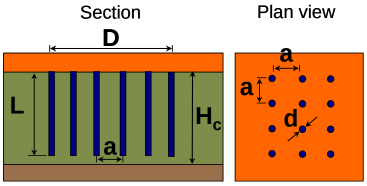
Here, subindexes refer to soil, inclusion and equivalent plane element properties; the equivalent plane element thickness, $t_{equivalent}$, is given by,

$$t_{equivalent} = \sqrt{12 \frac{(EI)_{equivalent}}{(EA)_{equivalent}}}$$

4. DYNAMIC BEHAVIOUR OF SOIL DEPOSITS WITH RIGID INCLUSIONS

A parametric study was carried out analyzing the dynamic response of two stratigraphic profiles that represent typical geotechnical conditions of the lake zone in Mexico City. The following parameters were used for these analyses:

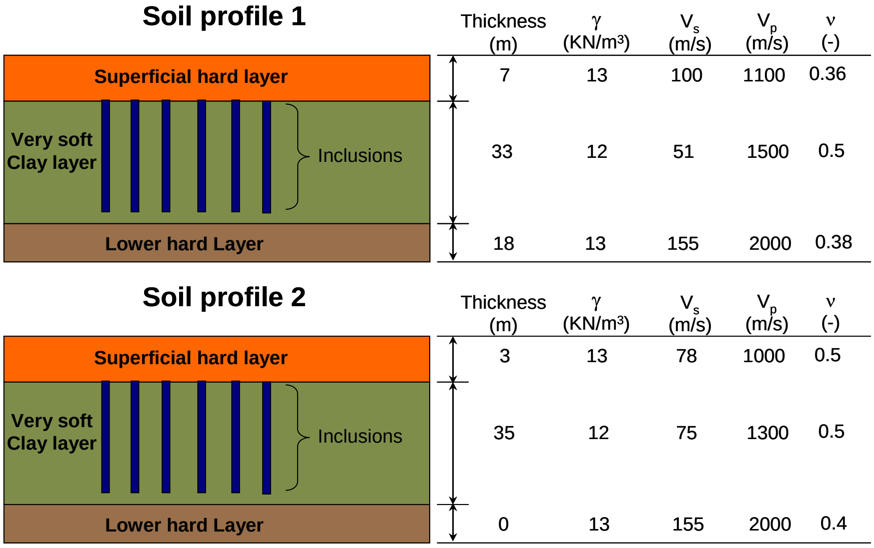
- Normalized spacing (a/d)
- Normalized width of the inclusion-added zone (D/H_c)
- Normalized length (L/H_c)
- End support conditions of the inclusion



where d is the equivalent diameter of the inclusion, a is the distance between inclusions, D is the inclusion zone width, H_c is the soft soil stratum thickness, and L is the inclusion length.

4.1 Studied Models

The two studied soil profiles are illustrated in Fig 4, where two very soft clay strata, 33 and 35m thick respectively, are limited by two hard layers with shear wave velocities of 51 and 75m/s, and soil deposit fundamental periods of 1.5 and 3s. Cylindrical concrete inclusions were assumed, having 0.4m in diameter and a length of 25m; other necessary properties were: EI = 9000KNm^2, and EA=5x10^{6}KN.



Soil profile 1

Thickness (m)	γ (KN/m³)	V_s (m/s)	V_p (m/s)	ν (-)
7	13	100	1100	0.36
33	12	51	1500	0.5
18	13	155	2000	0.38

Soil profile 2

Thickness (m)	γ (KN/m³)	V_s (m/s)	V_p (m/s)	ν (-)
3	13	78	1000	0.5
35	12	75	1300	0.5
0	13	155	2000	0.4

Symbols: γ=unit weight, V_s and V_p= shear and compression waves velocities, ν=Poisson's ratio.

Figure 4. Elastic and dynamic characterization of the soil profile conditions studied

Fig 5 shows an example of typical results obtained from the seismic response analyses in terms of acceleration histories at different depths and the corresponding response spectra obtained from them. Acceleration amplifications are observed as seismic waves travel upwards through the clay deposit; spectral ordinates are also amplified, particularly at periods of 0.75 and 1.9s.

4.2 Inclusion Spacing

Fig. 6 shows the response spectra of the soil deposit surface, at the central point of the inclusion-improved zone (point A). Spectral values were computed applying a seismic excitation at the base of the inclusion-added clay deposits for different inclusion spacing. As it can be seen, spectral ordinates reduce when inclusions are closely spaced, for periods larger than 1.5s, whereas spectral ordinates increase at smaller periods. This effect is more evident at point B, at the end of the inclusion zone, as seen in Fig. 7.

4.3 Width of the Improved Zone

Fig. 8 illustrates the effect of changing the inclusion-added zone width on spectral ordinates, for the two deposit conditions under study. Results indicate that spectral ordinates close to the deposit's fundamental period decrease, as the value of the quotient D/H_c increases, for constant values of the diameter and the inclusion spacing. These effects are particularly notorious for D/H_c>1.5. The fundamental period and the maximum acceleration are not affected when changing the width of the stiffened zone.

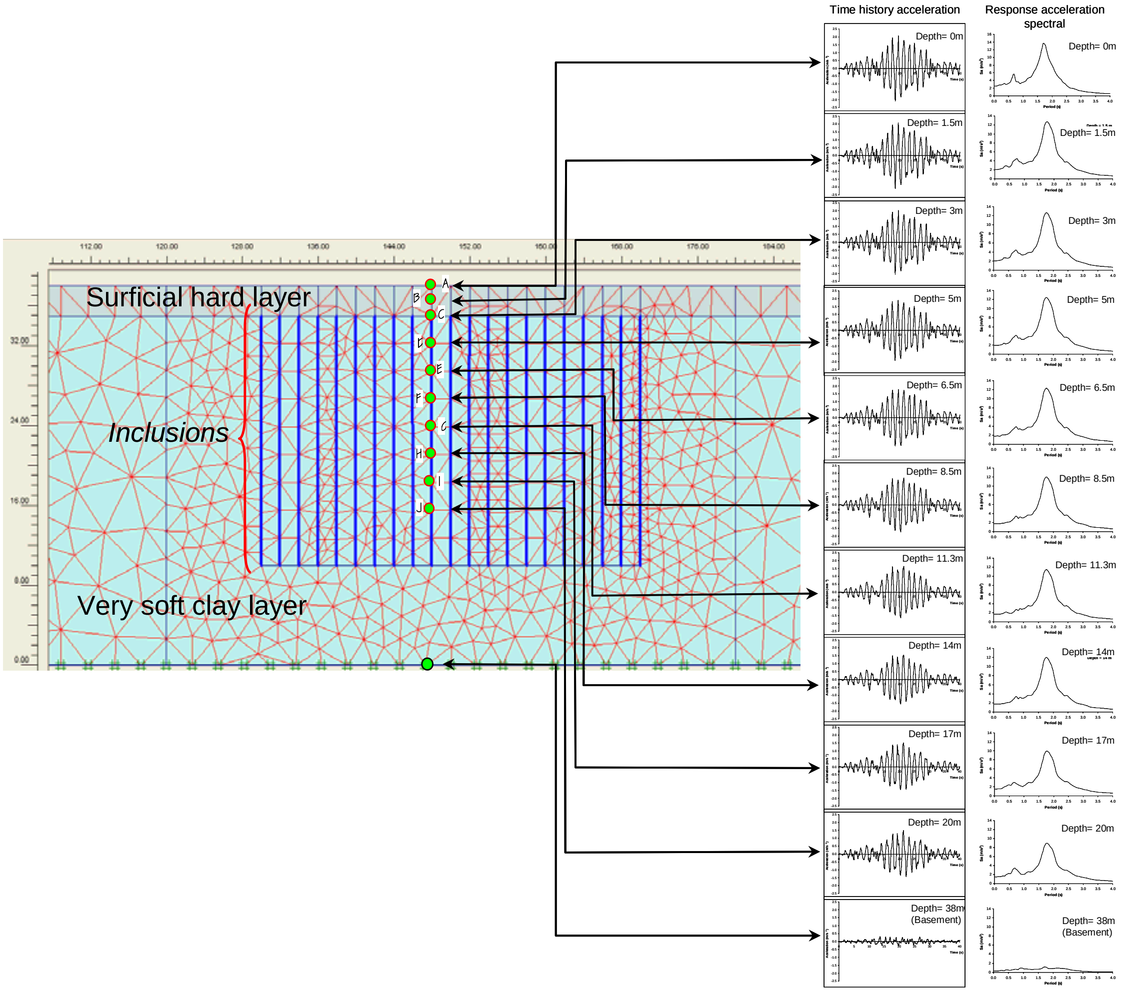


Figure 5. Acceleration time histories and response spectra at different depths

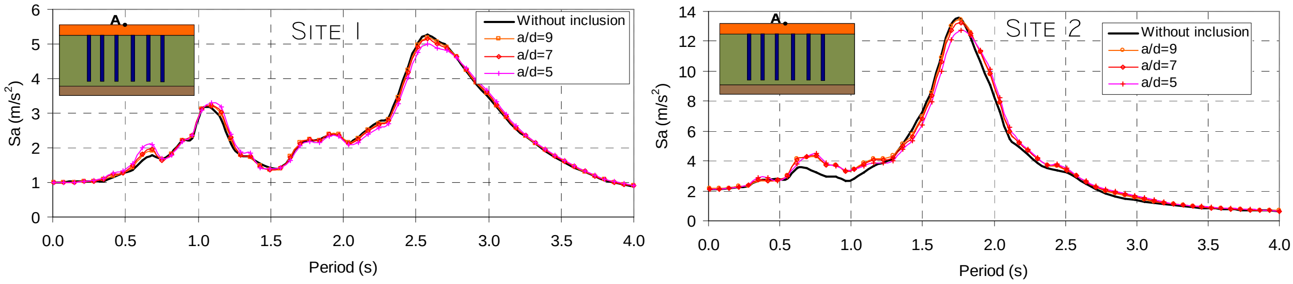


Figure 6. Response spectra calculated on the surface at a point in the centre of the zone improved with inclusions having different spacing

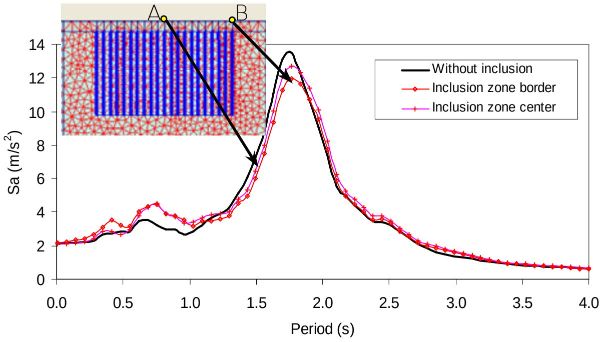


Figure 7. Response spectra at the centre and at the end of a clay deposit stiffened with inclusions separated 2m

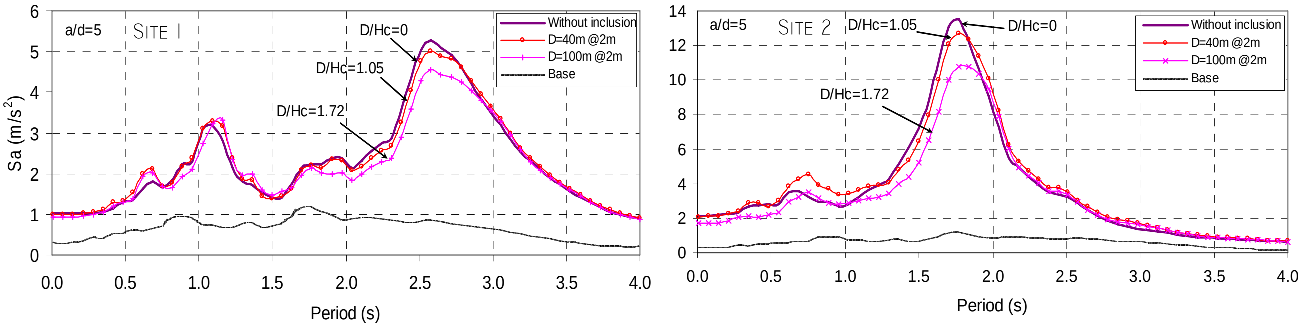


Figure 8. Calculated spectral response at the surface of the deposit for different widths of the improved zone

4.4 Support conditions

Fig. 9 illustrates the typical arrays in which inclusion ends may be supported when a soft clay stratum is confined by stiffer materials. Response spectra calculated for inclusions supported at the base and at the top of the clay deposit are compared in Fig 10 with the spectrum calculated for no inclusion. Spectral accelerations in the short period range amplify for the clay deposit stiffened with inclusions supported on the stiff bottom layer, and the opposite effect was noted for the case in which the inclusion heads were socketed into the upper stiff layer. Spectral amplifications around fundamental period of the soil deposit are not evident.

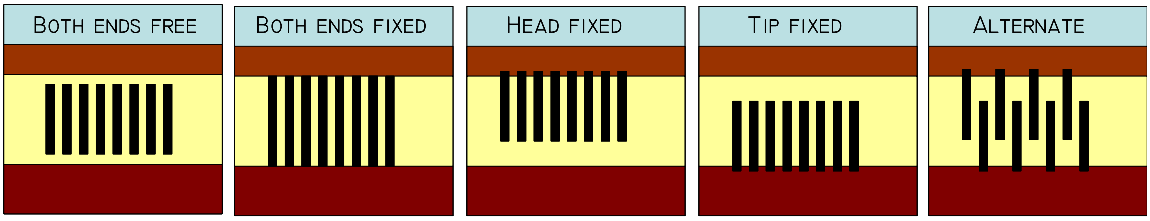


Figure 9. Support conditions for inclusions in a soft soil deposit confined by stiff soil layers

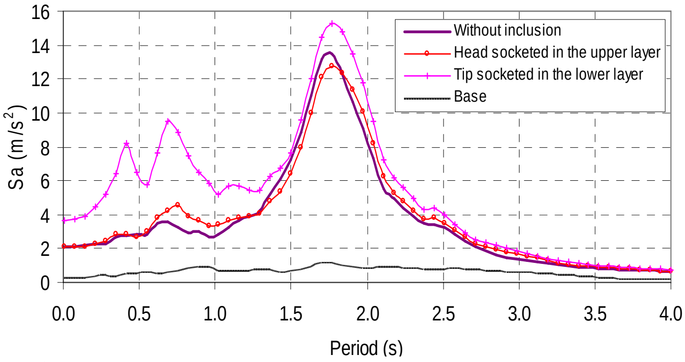


Figure 10. Response spectrums for a deposit with and without inclusions with heads supported at the upper stiff layer and inclusion tips supported at the bottom stiff layer

Fig 11 Shows the internal forces in an inclusion at the end of the dynamic load when its tip is fixed. It can be observed that maximum values are located at the tip of the inclusion. This result is very important because it could lead to a failure condition, depending on the magnitude of the dynamic load.

5. CONCLUSIONS

The results of the numerical analyses presented here are limited in scope and range. Consequently, the dynamic behaviour of soft clay deposits stiffened with rigid inclusions requires further study. Nevertheless, the following conclusions can be made from the analyses presented here:

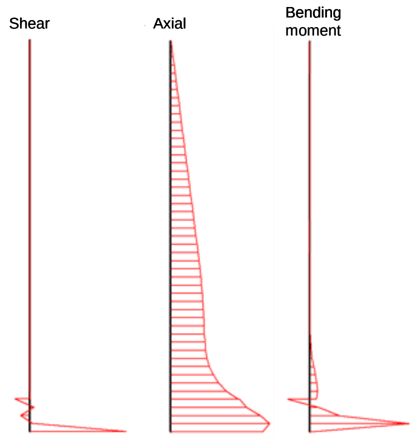


Figure 11. Shear and axial forces and bending moment in an inclusion at the end of the dynamic load when its tip is fixed

In general, the effects of inclusions on the dynamic behavior of the soil deposits are not significant. These effects are more important at the perimeter of the inclusion-improved zone.

For periods larger than 1.5s, larger spectral ordinates are obtained when normalized spacing decreases; the opposite trend was observed for shorter periods. As before, these effects are small at the central part of the improved zone and are much more evident peripherally.

Smaller spectral ordinates were obtained when increasing the normalized width, D/H_c, particularly around the soil deposit fundamental period. Increasing the normalized width resulted in no effect on the value of the deposit's fundamental period. However, it must be recalled that the soil was modeled as a linearly elastic material.

Support conditions at the tips and the heads of the inclusions have a major effect on the dynamic response of the clay deposits studied here. Spectral ordinates increased most notably in the short period range when the inclusion tips were socketed in the lower stiff material, and there is a high stress concentration that could produce failure of the inclusion. Therefore, fixed tip or similar solutions are not recommended from the dynamic point of view.

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