INNOVATIVE SITE RESPONSE ANALYSIS ACCOUNTING FOR GROUND IMPROVEMENTS

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ABSTRACT

Site response analyses (SRA) are crucial for evaluating the behavior of sensitive structures, such as nuclear facilities, under seismic loads. Typically, SRA are conducted in the frequency domain using 1D wave propagation models to determine the linear equivalent soil profile and the input signal at the base of the structure. In order to consider the non-linear strain-dependent behavior of soil, an iterative approach is required to achieve a compatible strain profile. While this method is effective for horizontally layered soil profiles, it is not suitable for configurations with soil reinforcement elements such as deep soil-mixing (DSM) or rigid inclusions (RI), whose presence modifies the overall response of the soil profile and introduces anisotropy.

Classic 1D wave propagation analyses are thus inadequate in the presence of reinforced soils due to the complex effects of the reinforcements on soil stiffness and wave propagation. Analytical homogenization formulae can give a preliminary estimate of the apparent shear stiffness of the reinforced medium but present several limitations such inadequacy to model the response near interfaces between soil layers or in the presence of important stiffness contrasts, and they are limited to specific reinforcement geometries. To address this question, the present study introduces a new iterative methodology combining 1D wave propagation analysis with 3D finite element (FE) modelling of the reinforced soil column to determine its equivalent shear modulus. This approach makes it possible to determine a strain-compatible soil profile suitable for SSI analyses, taking into account both strain-dependent soil behavior and the impact of soil improvements in terms of equivalent shear modulus.

INTRODUCTION

Within the context of SSI analyses, generally conducted by means of substructuring approaches (e.g. Kausel superposition theorem), site response analyses (SRA) are often conducted as a preliminary step to determine the linear equivalent soil profile and the input signal at different depths of the soil column.

Typically based on 1D wave propagation configurations and horizontally layered soil profiles, SRA is usually conducted in the frequency domain. Due to the non-linear strain-dependent behavior of soil, multiple iterations are required to achieve a strain-compatible soil profile. This approach has now become a standard procedure (Shake 91, 1992) and is well suited to configurations where the stratigraphy can be assimilated to a superposition of horizontal soil layers of infinite extension.

Ground improvement techniques, such as deep soil-mixing (DSM) or rigid inclusions (RI), are nowadays used to enhance bearing capacity and control settlement (ASIRI, 2012, AFPS and CFMS, 2012). However, these improvement techniques modify the behavior of the soil profile, introducing significant anisotropy with different changes of stiffness depending on the load direction, additional constraints on wave propagation that may impact the energy dissipation capacity of the reinforced medium, etc. These phenomena therefore need to be considered in the SRA.

This study presents a brief state of the art of existing analytical approaches for the homogenization of reinforced media, followed by the presentation and validation of a new SRA iterative methodology, combining 1D wave propagation modeling (e.g., Shake type models) with explicit 3D FE modeling of the improved soil column to determine the homogenized layer-by-layer deformability parameters of the reinforced soil. This approach allows SRA to account for both strain-dependent soil behavior and the impact of soil improvements in terms of equivalent shear modulus, and the determination of the corresponding strain-compatible soil profile, to be introduced in future SSI analyses (e.g., dynamic impedances).

ANALYTICAL FORMULAE TO ESTIMATE THE HOMOGENIZED SHEAR MODULUS OF REINFORCED SOIL

Several analytical homogenization approaches are available in the literature to estimate the homogenized shear modulus for simple reinforced configurations, such as column or cross trench arrangements (see Figure 1). For instance, Hashin (1983) proposed the following formula to estimate the homogenized shear modulus G_{hom}^{RI} of an isotropic homogeneous medium reinforced with vertical reinforcements of circular cross-section (i.e., rigid inclusions):

$$G_{hom}^{RI} \cong G_s + \frac{\alpha}{\frac{(1-\alpha)}{2G_s} + \frac{1}{G_r - G_s}} \tag{1}$$

Where α is the substitution rate, G_s the shear modulus of the soil and G_r the shear modulus of the reinforcement.

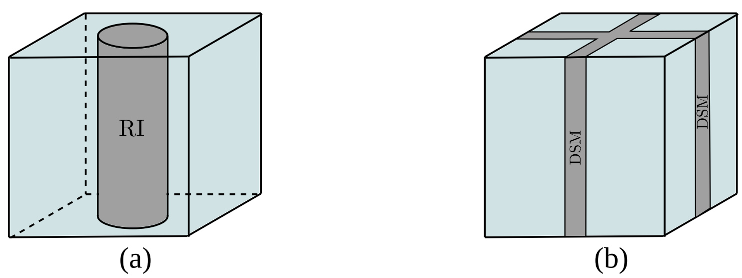


Figure 1 : Soil medium reinforced with (a) rigid inclusions and (b) DSM cross-trenches

The work of Gueguin et al. (2013) led to the following expressions for the homogenized shear modulus G_{hom}^{CT} of an isotropic homogeneous medium reinforced with cross trenches.

$$G_{hom}^{CT} \approx \frac{G^{LB} + G^{UB}}{2} \tag{2}$$

where:

$$G^{LB} = G_s \left[\frac{1-\alpha}{(1-\alpha) + \left(\sqrt{1-\alpha} - (1-\alpha)\right)\frac{G_s}{G_r}} + \left(1 - \sqrt{1-\alpha}\right)\frac{G_r}{G_s} \right] \tag{3}$$

$$G^{UB} = G_r \left[\frac{\sqrt{1-\alpha} + \frac{G_r}{G_s}\left(1 - \sqrt{1-\alpha}\right)}{\left(\alpha - 1 + \sqrt{1-\alpha}\right) + \frac{G_r}{G_s}\left(2 - \alpha - \sqrt{1-\alpha}\right)} \right] \tag{4}$$

Despite the simplicity of use of these homogenization approaches, they exhibit two main limitations. First, they are primarily designed for isotropic homogeneous soil configurations and do not account for interfaces between soil layers with significant stiffness contrasts. Second, the reinforcement geometries considered in existing formulations (e.g., circular columns or cross-trench arrangements) do not always align with real-world configurations, restricting their applicability.

NUMERICAL APPROACH TO DETERMINE THE HOMOGENIZED SHEAR MODULUS OF REINFORCED SOIL

Analytical homogenization approaches are inherently limited by simplifying assumptions that may not adequately represent the complexity of reinforced soil configurations. As a result, the use of numerical approaches (i.e., finite elements) is necessary to accurately capture the effects of a given soil improvement configuration and soil stratigraphy in the apparent shear modulus of each soil layer. Therefore, explicit 3D finite element models (Code_Aster, 2002) of the improved soil columns are used in the present study.

Model description

The soil reinforcements (rigid inclusions or DSM cross-trenches) and the surrounding soil are explicitly modelled by volume elements. No interface is considered between the soil and the reinforcement elements. The nodes at the base of the column are fixed and kinematic constraints are applied on both sides of the soil column to simulate periodic boundary conditions. A scheme of the FE model is illustrated in Figure 2 (a) and (b).

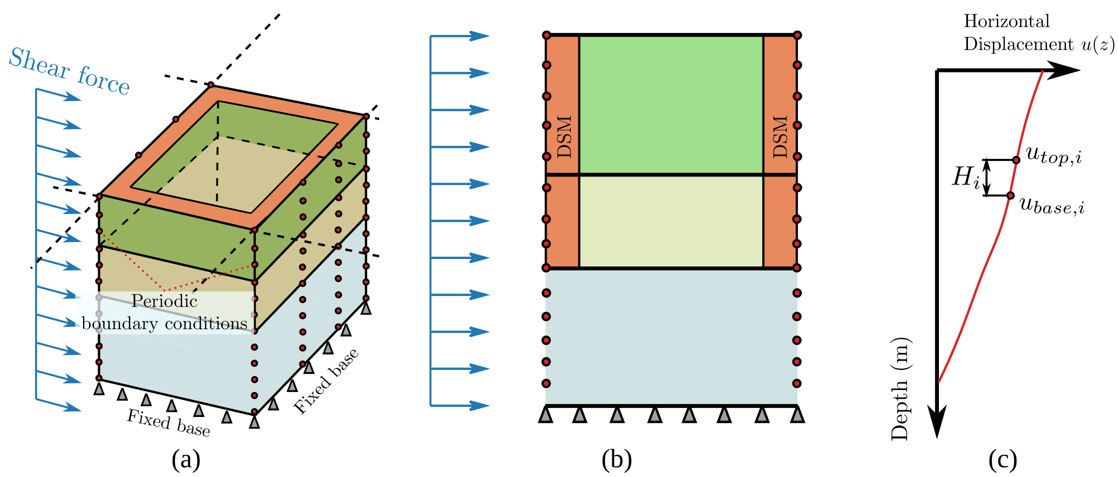


Figure 2 : Principle of a 3D FE modelling of a DSM-improved soil column: (a) model of a soil column reinforced by DSM under shear stress, (b) cross-section and (c) horizontal displacement profile

The seismic loading is introduced by means of a horizontal uniform acceleration, applied as a static volumetric force over the entire height of the reinforced soil column. Since the model remains linear elastic, only the deformation is relevant for determining the homogenised shear modulus G_{hom} at each layer of the soil column, as the difference in displacement between the top and the base of the layer $u_{top,i} - u_{base,i}$, divided by its thickness H_i, as described in Figure 2 (c).

Given the shear force F_i acting on the layer, the corresponding shear stress τ_i may be obtained by dividing F_i by the cross-section area A of the soil column, which remains constant along its height. The homogenous shear modulus $G_{hom,i}$ is then estimated using the following expression:

$$G_{hom,i} = \frac{\tau_i}{\gamma_i} \approx \frac{F_i/A}{(u_{top,i} - u_{base,i})/H_i} \tag{5}$$

The shear force F_i can be determined by multiplying the total mass of the soil layers above the layer i by the unit horizontal acceleration applied to the soil column. The displacements at the top and bottom of each layer are computed as the average of the node displacements at the corresponding depths.

The soil profiles considered in this study are designed to represent configurations encountered in real projects:

- Profile I: a multilayer soil profile with a 20 m thick, soft soil layer (Soft Soil 1).
- Profile II: based on Profile I, but with an additional 2 m thick intermediate layer of less soft soil (Soft Soil 2) embedded in the soft soil layer (Soft Soil 1).

In both cases, a 20 m thick layer of hard soil is placed between the soft soil and the semi-infinite bedrock, and a 2 m thick load transfer platform (LTP) lies at the surface. A schematic representation of these soil profiles is provided in Figure 3, with the corresponding mechanical properties listed in Table 1. The mechanical properties of the reinforced concrete rigid inclusions and of DSM reinforcement are also given.

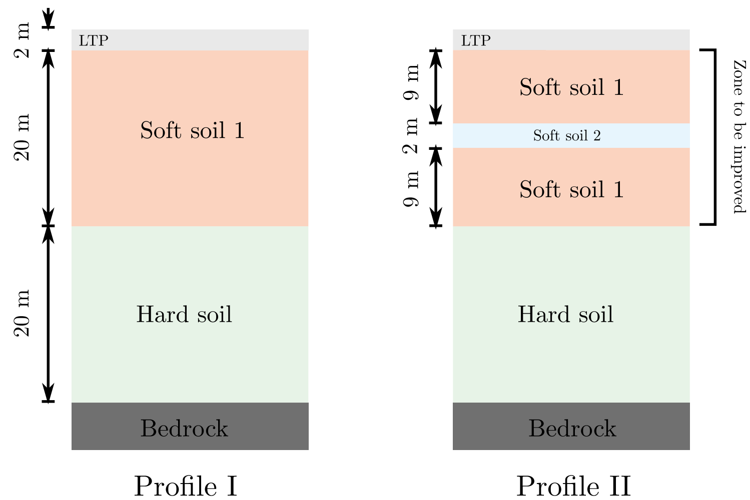


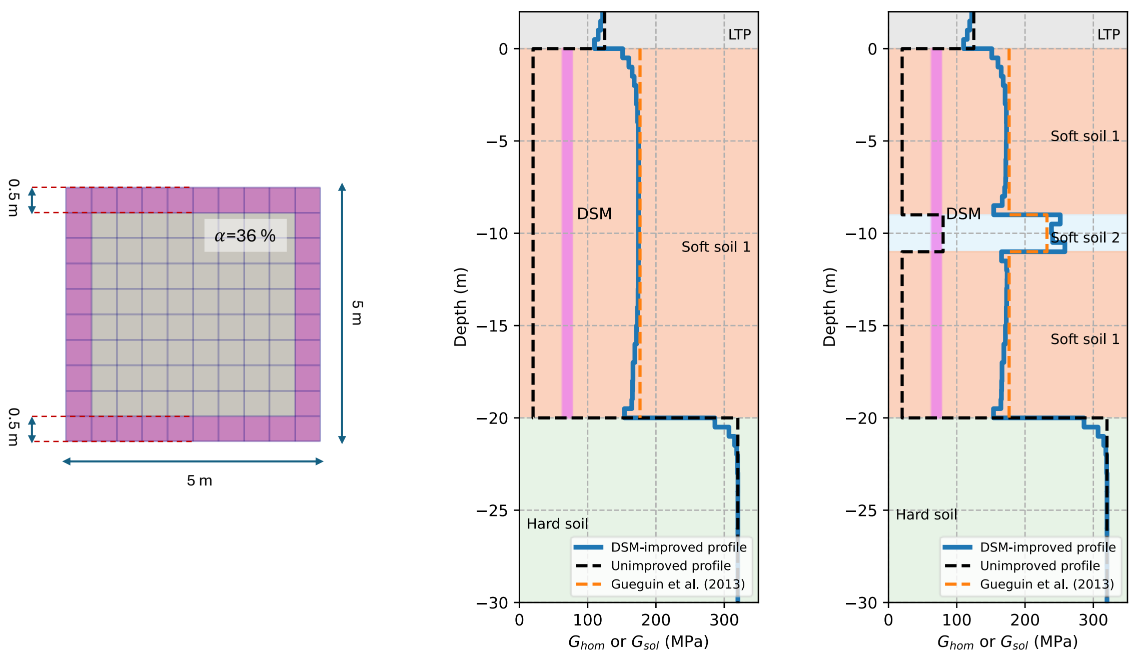
Figure 3 : Schemes of the proposed soil profiles

Table 1 : Mechanical properties of the soil and the reinforcements used in the analyses

	Soft soil 1	Soft soil 2	Hard soil	Bedrock	LTP	RI	DSM
Shear modulus G (MPa)	20	80	320	2880	125	12500	720
Young's modulus E (MPa)	58	232	982	7776	362.5	30000	1872
Shear wave velocity Vs (m/s)	100	200	400	1200	250	2236	600
Poisson ratio ν (-)	0.45	0.45	0.45	0.35	0.35	0.2	0.3
Mass density ρ (t/m^3)	2	2	2	2.2	2	2.5	2

Reinforcement configuration with DSM cross-trenches

The DSM-reinforcement configuration consists of reinforcing 20 m of soft soil with 1 m thick DSM walls, spaced 5 m apart, which corresponds to a substitution ratio of 36%. The improved section is presented in Figure 4 (a). The two soil profiles, illustrated in Figure 3, are considered in the study. The homogenised shear modulus G_{hom} of the reinforced soil column is evaluated using both an explicit FE modelling and the analytical solution proposed by Gueguin et al. (2013).



(a) (b) (c)

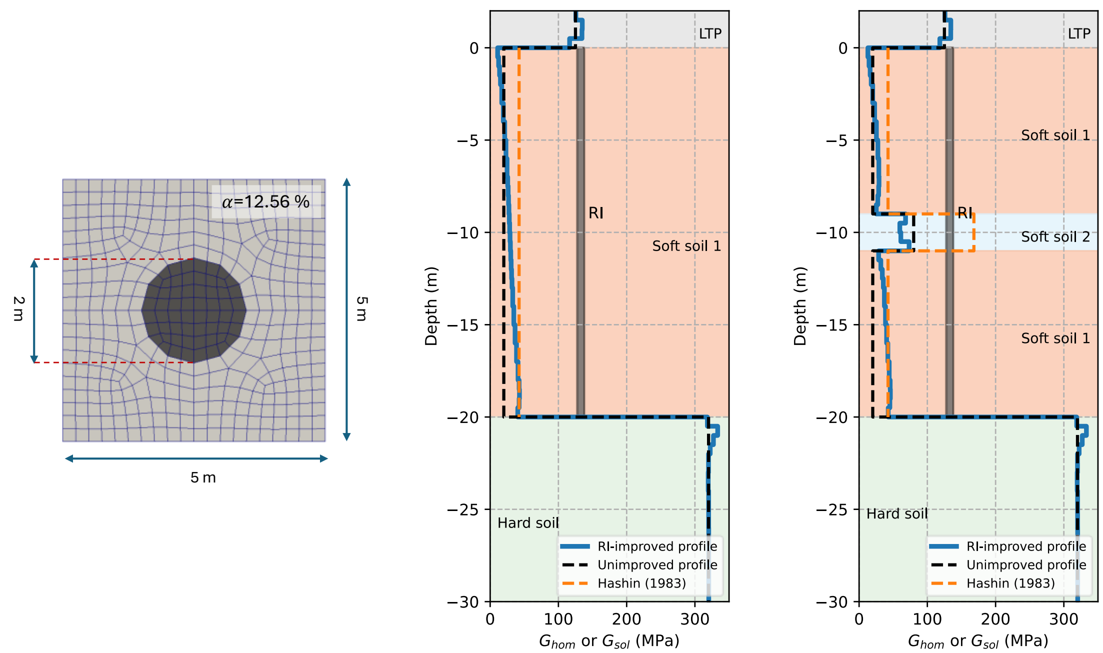
Figure 4 : Comparison of homogenization approaches for a DSM cross-trench reinforcement: (a) plan view of the reinforced soil section modelled with FE (soil-mixing in magenta and soil in grey), and comparison of the homogenized shear modulus profiles for (b) the profile I and (c) the profile II

The comparison of the results obtained using both homogenization approaches for Profile I and Profile II, respectively, is presented in Figure 4(b) and (c). Notably, both approaches yield very similar homogenized shear moduli G_{hom} at the middle part of the reinforced soft soil layers. However, near the soil layer interfaces, several differences emerge between the numerical model and the analytical formulation, indicating that interface effects are not fully captured by the analytical approach. Therefore, to account for this particularity in the site responses analyses of a reinforced soil by cross-trench configuration, the numerical approach should be preferred

Reinforcement configuration with circular RI

A reinforcement configuration comporting cylindrical rigid inclusions is also studied using the two soils profiles illustrated in Figure 3. The reinforcement consists of reinforced concrete columns of 2 m in diameter, arranged in a 5 m pattern. The RIs have a length of 20 m, extend through the soft soil layer and their tips lie at the top of the hard soil layer. This configuration results in a substitution ratio of 12.6%.

The results, shown in Figure 5 (b) and (c), indicate that the analytical solution is not able to accurately estimate the right value of the homogenized shear module. Furthermore, differences with respect to the numerical solution increase in the proximity of soil layer interfaces comporting a stiffness contrast, with analytical estimates that may underestimate or overestimate the homogenized shear module. Additionally, the shear modulus of the soil in the proximity of the reinforcement may also be affected by the presence of the RI. This phenomenon is only captured by the finite element model.



(a) (b) (c)

Figure 5 : Comparison of homogenization approaches for a RI reinforcement: (a) plan view of the reinforced soil section modelled with FE (IR in dark grey, soil in light grey), and comparison of the homogenized shear modulus profiles for (b) the profile I and (c) the profile II

Summary

In view of the previous results, it can be concluded that the analytical solutions generally do not adequately consider soil stratigraphy and stiffness contrasts, at least for the reinforcement configurations addressed in this study. The differences between these two configurations in terms of deviation from the numerical estimation can be partially attributed to the significantly high shear modulus of the RI-reinforcement which is made by reinforced concrete rather than DSM. Consequently, when stiffness contrasts exist between the soil layers and between the reinforcement and the in-situ soil, numerical solutions by means of FE models are preferable for a more accurate assessment of the equivalent shear modulus of the improved medium.

INNOVATIVE SITE RESPONSE ANALYSIS METHODOLOGY ACCOUNTING FOR GROUND IMPROVEMENTS

Coupled 1D/3D SRA methodology

In SRA based on the equivalent linear method, such as Shake 91 (1992), an iterative resolution scheme is employed to account for strain-dependent soil stiffness and damping. This ensures that the soil stiffness and damping properties are continuously updated to reflect the expected strain levels during an earthquake. The calculations, performed using a 1D model of the soil profile, are typically conducted in the frequency domain.

In the case of a reinforced soil, the ground improvement elements affect the strains levels experienced by the soil and thus the resulting stiffness, damping, and wave propagation through the reinforced medium. Analytical formulae may be used in some cases as a first estimate of the homogenized equivalent moduli combined with a 1D wave propagation analysis. However, as already shown above, some discrepancies may arise in the presence of large stiffness contrast between several soil layers or between the soil and the reinforcement. One possibility is to undertake the site response analyses directly by means of a full FE analysis which, although more accurate, can be time-consuming and expensive due to the iterative nature of the calculations and the larger size of the required numerical models.

An intermediate approach is proposed in the present study, allowing to account for the impact of soil improvement on the equivalent shear modulus while considering the site stratigraphy and the real reinforcement configuration. A coupled 1D/3D SRA methodology is introduced which leverages the advantages of both types of numerical modelling. It combines 1D wave propagation modelling, which ensures efficiency in iterative calculations, with 3D FE modelling, which provides high accuracy in estimating the homogenized shear modulus of the reinforced soil. The principle of this iterative 1D-3D SRA is illustrated in Figure 6 for a DSM-based cross-trench improvement but applies to other types of ground reinforcement, such as RI or stone columns.

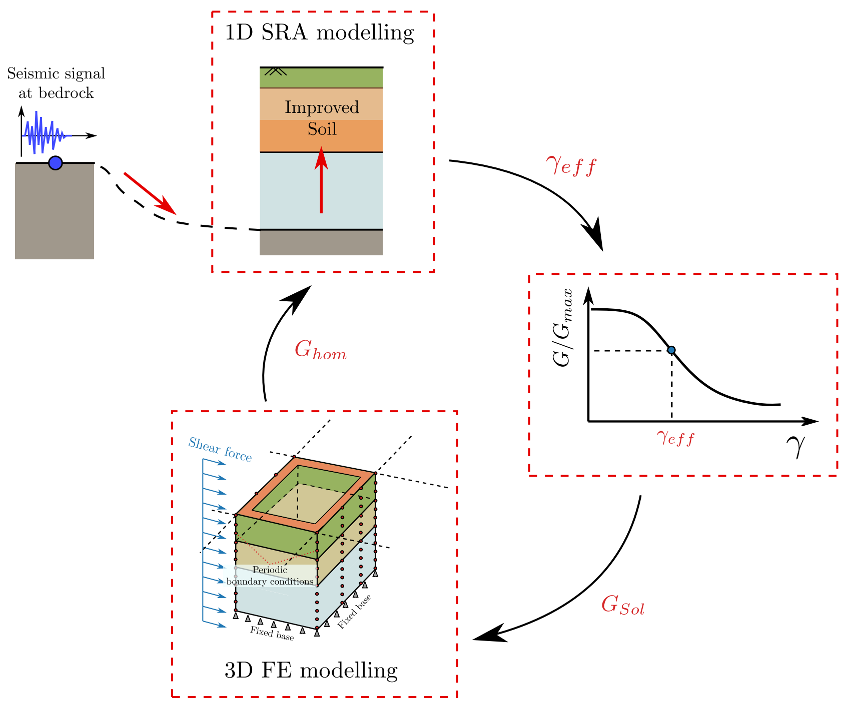


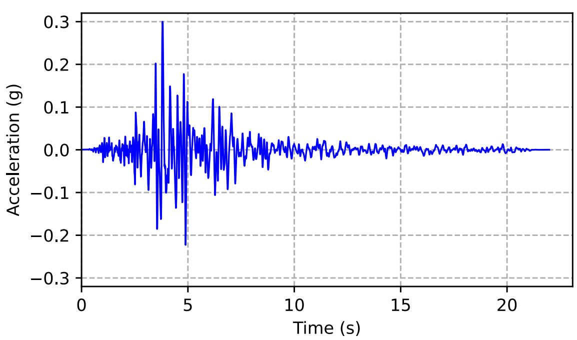
Figure 6 : Principle of the coupled 1D/3D SRA methodology applied to the site response analysis of a DSM-based cross-trench reinforcement

As illustrated in Figure 6, this methodology is also based on an iterative procedure that, at each iteration, performs a 1D wave propagation analysis using the equivalent linear soil profile from the previous iteration and an explicit 3D FE model of the reinforced soil column to estimate the homogenized shear modulus to be used in the calculation of the next iteration :

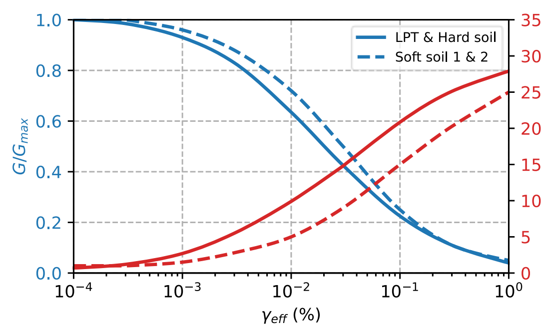
- In the first iteration, an elastic 1D wave response analysis is performed on the unimproved soil profile to determine the effective strain levels γ_{eff} in each layer. Based on these strains, the compatible shear modulus of the soil G_{sol} is determined using the soil degradation curves G/G_{max}.
- The calibrated shear modulus G_{sol} is then introduced in the 3D FE model of the improved column, used to determine the equivalent shear modulus of the reinforced soil G_{hom}. This homogenized soil profile is then introduced into the 1D wave response analysis to determine the effective strain profile γ_{eff} for the equivalent soil column.
- Based on this strain γ_{eff}, the homogenized shear modulus G_{hom} is recalculated and reintroduced into the explicit FE model of the improved soil column to calculate the new equivalent shear modulus. The procedure is repeated iteratively until the relative error between the homogenized shear modulus profiles of two consecutive iterations is less than 5%.

Numerical case-study

The proposed coupled 1D/3D SRA methodology is applied to the study of a DSM cross-trench reinforcement configuration. The soil profile II illustrated in Figure 3(b) is considered. A natural seismic recording, Friuli (1976) scaled to 0.3g, is considered at the bedrock outcrop (see Figure 7 (a)). The stiffness degradation and damping relationships for the soils are described by the curves illustrated in Figure 7 (b), which are based on the works of Seed and Idriss (1970) and Vucetic and Dobry (1991).



(a)



(b)

Figure 7 : (a) Friuli (1976) earthquake scaled to 0.3g and (b) stiffness degradation and damping relationships for the soil

The 1D wave propagation step is performed using Shake 91 (1992), while the 3D FE model used to homogenize the reinforced soil is carried out with Code_Aster (2020). An unreinforced soil profile with the same stratigraphy is also analyzed using Shake and presented for comparison purposes.

The evolution of the homogenized shear modulus G_{hom} considered at each calculation iteration is presented in Figure 8 (a) along with the corresponding equivalent shear modulus of the soil at the end of the analysis. Convergence is achieved after five iterations, demonstrating the efficiency of the proposed methodology. The comparison between the homogenized shear modulus and that of the soil highlights the significant increase in shear stiffness due to the DSM cross-trench improvement.

The equivalent linear soil profiles for both the DSM-improved and unreinforced configurations are presented in Figure 8 (b). These profiles can serve as input data for dynamic analyses, such as impedance calculations. The presence of DSM fundamentally alters the site's dynamic behavior, which undergoes much less overall degradation than in the unreinforced case. Compared with the unreinforced case, stiffness degradation is more evenly distributed. Reinforcement therefore helps to homogenize stiffness contrasts between soil layers, making wave propagation analyses less subject to local amplifications, resonance and other equivalent phenomena.

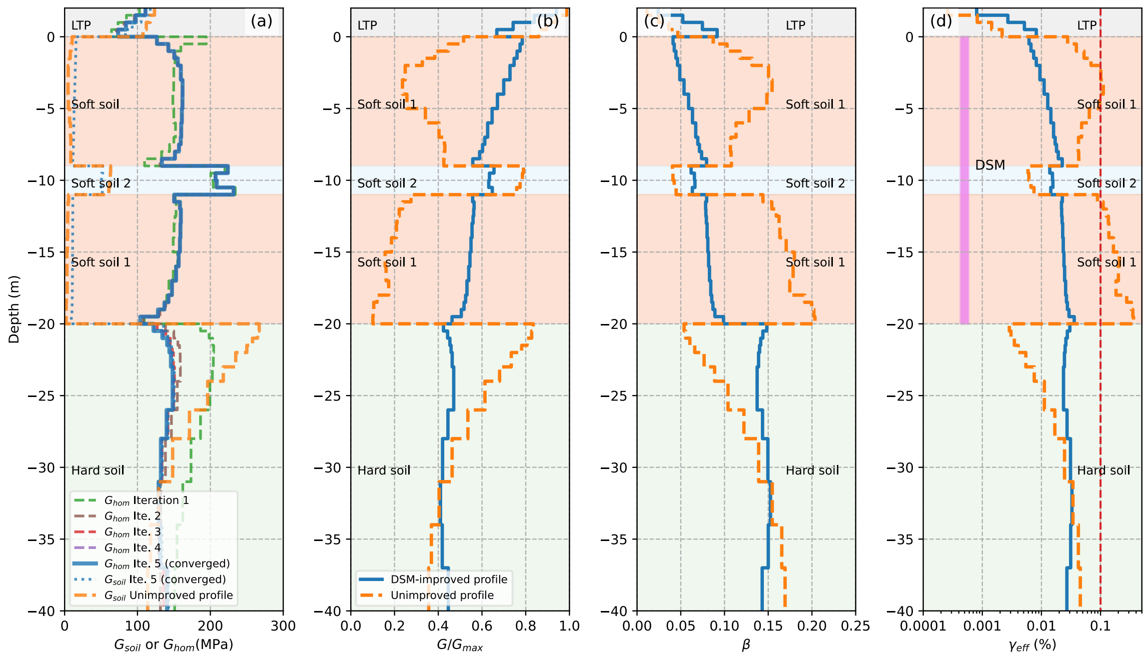


Figure 8 : Comparison of site response analysis results between a DSM cross-trench reinforcement and an unreinforced profile

The same trend is observed in terms of the effective shear deformation profile, whose values are more uniformly distributed in the reinforced configuration with a lower maximum amplitude. Finally, it can be observed that in the present case, the unreinforced profile exceeds a strain value of 0.1%, which is generally considered as the limit up to which the equivalent liner assumption remains valid. Soil reinforcement places the case within the limit of acceptable shear deformation values, enabling wave propagation analyses to be conducted by means of equivalent linear approach instead of more complex numerical ones.

CONCLUSION

This article presents a novel site response analysis methodology incorporating soil reinforcement and stratigraphy effects. First, existing analytical formulae for estimating the equivalent shear stiffness of a reinforced soil medium are reviewed. Then, a comparative study between finite element modelling and these analytical approaches is carried out to highlight the limitations of the latter, unable to take interface effects into account. The new coupled 1D/3D site response analysis methodology is introduced and explained. Finally, a numerical case study is conducted to illustrate the interest of this new approach for conducting site response analyses in the presence of reinforced soils. It is demonstrated that this method offers rapid convergence and direct access to the input data required for subsequent analyses steps within the framework of a substructuring modelling of soil-structure interaction (i.e., impedance functions). Furthermore, this new approach remains in the continuity of classic 1D site response analyses.

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