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A 3D macro-element for Soil-Structure Interaction

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Abstract

This paper presents a 3D non linear interface element able to compute Soil-Structure Interaction (SSI). Several approaches exist to take this phenomenon into account: the following work is based on the “macro-element” concept. The particularity of the macro-element lies in the fact that the movement of the foundation is entirely described by a system of generalised variables (forces and displacements) defined in the foundation centre. The non linear behaviour of the soil is reproduced using the classical theory of plasticity. The failure surface is defined using an adequate overturning mechanism. The element is able to simulate the 3D behaviour of a rigid shallow foundation under static and dynamic loadings considering uplift. It is implemented into [FEDEASLab](#), a finite element [MATLAB](#) toolbox. Comparisons with experimental results under cyclic and dynamic loadings show the good performance of the approach.

Introduction

In order to study Soil-Structure Interaction (SSI), several methods exist: the macro-element approach consists in condensing all non linearities into a finite domain and works with generalised variables (forces and displacements) that allow simulating in a simplified way the behaviour of shallow foundations. Several 2D macro-elements exist in the literature [1], [5]. The 2D macro-element developed by Crémer [1] can be used for static/cyclic but also dynamic loading (i.e. earthquake) applied in the horizontal direction, considering the plasticity of the soil and the uplift of the foundation.

Inspired on this last work, a new 3D macro-element is developed hereafter. The goal is to compute the 3D behaviour of a circular, rectangular or strip shallow and rigid foundation lying on an infinite space submitted to a static or a dynamic loading. In the new version the macro-element takes into account the plasticity of the soil and the uplift of the foundation. It is implemented into [FEDEASLab](#), a finite element [MATLAB](#) toolbox. After the mathematical description of the macro-element, numerical results compared with experimental tests under cyclic and dynamic loadings are provided to show the good performance of the approach.

Shape of the foundation and associated kinematics variables

Being a macro-element, the foundation is supposed infinitely rigid and all non-linearities are condensed in a representative point: its centre. Within that framework it is appropriate to work with generalized (global) variables: the vertical force V , horizontal forces H_x , H_y , and moments M_x , M_y but also the corresponding displacements: vertical settlement u_z , horizontal displacements u_x , u_y , and rotations θ_x , θ_y . Torque moment (M_z) is not taken into account.

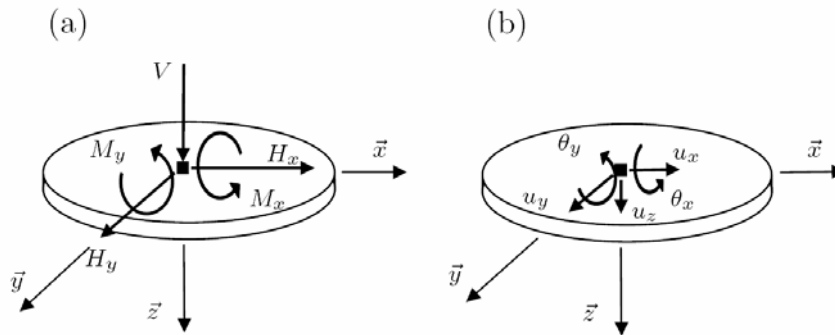


Figure 1. Shape of the foundation and global variables: (a) forces and (b) displacements

All the developments presented hereafter consider a circular foundation (Figure 1). Indeed, because of the symmetry of revolution, the horizontal loads in the directions x and y can be computed in a similar way. Furthermore, with this shape it is easier to reproduce the interaction between horizontal forces and moments. Nevertheless, an adequate normalisation of the variables [4] allows simulating the behaviour of rectangular but also stripping shallow and rigid foundations.

Two non linear mechanisms: plasticity and uplift

Decomposition of the non linear mechanisms

The 3D SSI macro-element takes into account three different mechanisms: elasticity, plasticity of the soil and uplift of the foundation. The total displacement must thus be decomposed as a sum of an elastic, plastic and uplift part.

Uplift is the result of rocking, i.e. the fact that the foundation rotates according to θ_x or θ_y (a part of the foundation loses contact with the soil) and the negative vertical displacement of the centre of the foundation. In order to compute uplift, the simple plasticity of the soil is not sufficient and a new non linear mechanism must be introduced to the macro-element. Plasticity and uplift are strongly coupled [3].

Mathematical description of the 3D macro-element

Elastic behaviour

The constitutive law can be written as $\vec{F} = K^{el}(\vec{u} - \vec{u}^{pl})$, where the displacement and force vectors are dimensionless according to [4]:

$$\vec{F} = (V' \quad H'_x \quad M'_y \quad H'_y \quad M'_x), \quad \vec{u} = (u'_z \quad u'_x \quad \theta'_y \quad u'_y \quad \theta'_x)$$

Normalisation of the displacements and the forces is done in different ways considering the shape of the foundation (circular or rectangular or strip). For each type of foundation displacements and forces are conjugated to calculate the work [3], [4]. This normalisation allows using the same equations whatever the shape of the foundation.

The elastic stiffness matrix is calculated using the real part of the static impedances [4]. It is considered diagonal, i.e. there is not coupling between the different directions of the loading.

Plastic behaviour

Failure criterion and loading surfaces

The failure criterion is defined for an overturning mechanism with uplift. It comes from [6] and it has been used already in the 2D macro-element presented in [1]. This criterion was initially developed for a shallow strip and rigid foundation in 2D lying on a half space of homogeneous cohesion. However, one can show that the shapes of the load and failure surfaces for a circular footing are very similar [4]. Thanks to the symmetry of revolution, the adaptation in 3D is very simple and consists in adding 2 terms in relation with the dimensionless horizontal force H'_x and the moment M'_y to obtain a 5D surface.

The loading surface used was initially developed in [1] to describe the behaviour of a 2D shallow foundation. The adaptation for the 3D macro-element is again simple. One finally obtains the following 5D surface:

$$f_c(F, \vec{\tau}, \rho, \gamma) \equiv \left(\frac{H'_x}{\rho a V'^c (\gamma - V')^d} - \frac{\alpha}{\rho} \right)^2 + \left(\frac{M'_y}{\rho b V'^e (\gamma - V')^f} - \frac{\beta}{\rho} \right)^2 + \left(\frac{H'_y}{\rho a V'^c (\gamma - V')^d} - \frac{\delta}{\rho} \right)^2 + \left(\frac{M'_x}{\rho b V'^e (\gamma - V')^f} - \frac{\eta}{\rho} \right)^2 - 1 = 0 \quad (1)$$

The coefficients a, b define the size of the surface in the planes $(H' - M')$, c, d, e and f define the parabolic shape of the surface in the planes $(V' - M')$ and $(V' - H')$.

These parameters can be fitted to different experimental results found in the literature. The denominators for the horizontal forces (the moments) are the same. Therefore, the interactions between the two horizontal forces (moments) are described by circles.

$\vec{\tau} = (\alpha, \beta, \delta, \eta)$ is the kinematics hardening vector composed of the 4 kinematics hardening variables and ρ the isotropic hardening variable. The variable γ is chosen to parameterize the second intersection point of the loading surface with the V' axis (the other point is the origin of the space) and its evolution in the V' axis.

The evolution of the hardening variables is obtained considering experimental results and numerical simulations [1] of foundations under cyclic loadings. A detailed description of the plasticity mechanism is given in [3].

The failure criterion is given by equation (1) by substituting $(\alpha, \beta, \delta, \eta, \rho, \gamma) = (0, 0, 0, 0, 1, 1)$

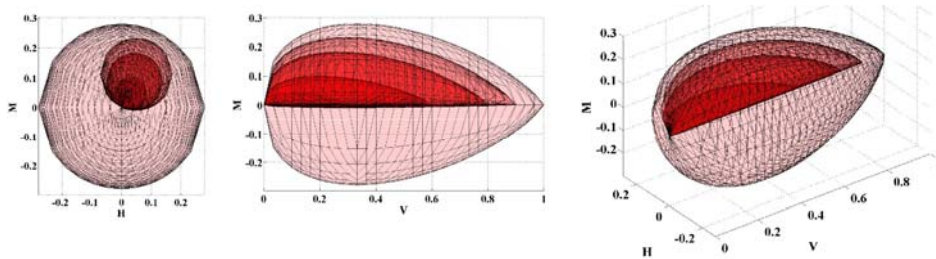


Figure 2. Loading surfaces and failure criterion in the planes $(H'_x - M'_y)$, $(M'_y - V)$ and in the space $(H'_x - M'_y - V)$

Uplift behaviour

The uplift mechanism presented hereafter describes in a phenomenological way the uplift behaviour originally developed in [1]. It does not take into account geometrical changes as the modification of the contact area between the soil and the foundation. Indeed, a change of the geometry can not be reproduced with the macro-element being just a point.

Uplift behaviour is taken into account by a unique variable δ representing the percentage of the surface of the uplifted footing. Moreover, we assume that uplift behaviour is not influenced by the horizontal forces.

Failure criterion and loading surfaces

For the uplift mechanism, failure occurs when the foundation is completely detached of the soil, in other words when $\delta=1$. A simple analysis for different shapes of foundations (circular or rectangular or strip) lying on elastic soil allows finding the relation $M'=V'/2$ between the overturning moment and the given vertical force. This equation can be actually considered as a failure criterion.

On a plastic soil, the relationship between the overturning moment and the vertical force is more complicated [1]. The overturning moment is also linked with the shape of the foundation. Thus, for a loading in two different directions (for $M'>0$ and $M'<0$) we obtain [4]:

$$f_{\infty} \equiv M'^2 - \left(\frac{V'}{q_1} (e^{-AV'} + q_2) \right)^2 = 0 \quad (2)$$

Where A is a parameter of the constitutive law and (q_1, q_2) a couple of integers taking into account the shape of the foundation.

The uplift behaviour is a non-linear, non reversible mechanism. Moreover, unloading does not follow an elastic linear behaviour. The evolutions of the loading surfaces are thus more complicated than for a classical plasticity model; they are activated even during unloading. Nevertheless, an initial elastic domain exists (except if the loading is strong in a direction which leads to a high plastification of the soil implying a total suppression of the elastic domain). This behaviour is physically translated into a residual uplift at each part of the foundation due to the plastification of the soil [4]. In order to activate the loading surfaces in loading but also in unloading, their mathematical expression is chosen to be always positive whatever the sign of the loading. Thus, the hardening variable β , a function between δ and δ_{max} (maximal uplift reached during the loading), evolves during loading and unloading. This evolution is given in [4].

The mathematical expression of the loading surfaces is given by equation (3) for loadings piloted by positive moments β^{\oplus} and negative moments β^{\ominus} . These two directions are in principle independent. The surface defining the elastic limit is also necessary to define. Indeed the loading surfaces being always positive, a test on the elastic surface allows knowing in which mechanism (uplift or elastic) is the model. The elastic limit is a function of the maximum percentage δ_{max} of uplift reached during the loading. The mathematical expression is given in equation (3):

$$\left\{ \begin{array}{l} f^{\oplus} \equiv \left| M' - \left(\frac{V'}{q_1} (e^{-AV'} + q_2 \beta^{\oplus}) \right) \right| = 0 \\ f^{\ominus} \equiv \left| M' + \left(\frac{V'}{q_1} (e^{-AV'} - q_2 \beta^{\ominus}) \right) \right| = 0 \end{array} \right. \text{ and } \left\{ \begin{array}{l} f_{el}^{\oplus} \equiv M' - \frac{V'}{q_1} q_2 \delta_{max}^{\oplus} (1 - \eta) - \frac{V'}{q_1} e^{-AV'} = 0 \\ f_{el}^{\ominus} \equiv M' - \frac{V'}{q_1} q_2 \delta_{max}^{\ominus} (1 - \eta) + \frac{V'}{q_1} e^{-AV'} = 0 \end{array} \right. \quad (3)$$

The graphical representation of all the surfaces is given in figure 3.

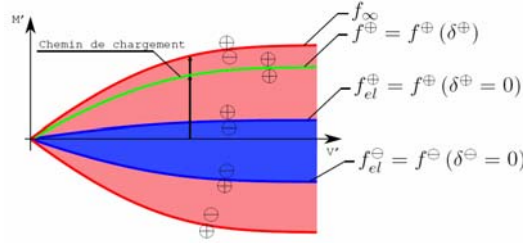


Figure 3. Loading surfaces, failure criterion and elastic limits with their signs.

If residual uplift occurs on both sides of the foundation, this implies that the elastic domain has entirely disappeared. The mechanisms \oplus and \ominus can in principle be activated simultaneously. Conditions allow choosing activated mechanisms are given by the equations:

$$\left\{ \begin{array}{l} f_{el}^{\oplus} \leq 0 \cup f^{\oplus} = 0 \Leftrightarrow \text{elasticity} \\ f_{el}^{\oplus} \geq 0 \cap f^{\oplus} > 0 \Leftrightarrow \text{uplift} \end{array} \right. \text{ and } \left\{ \begin{array}{l} f_{el}^{\ominus} \leq 0 \cup f^{\ominus} = 0 \Leftrightarrow \text{elasticity} \\ f_{el}^{\ominus} \geq 0 \cap f^{\ominus} > 0 \Leftrightarrow \text{uplift} \end{array} \right. \quad (4)$$

The adaptation in 3D of the uplift mechanism consists in defining a similar mechanism in the other horizontal direction. The two directions are coupled by considering a projection of the moments in the principal base [4].

Coupling of the plasticity and the uplift mechanism is done following the classical theory of the multi-mechanisms [4].

Numerical simulations and comparisons with experimental results

Cyclic behaviour

Within the European program TRISEE, experimental tests are performed on a shallow 1m x 1m rectangular foundation lying on sand [7]. Two tests are presented hereafter with two types of sand (High density sand (HD), and Low density sand (LD)). Figure 4 shows the comparison of the experimental with the numerical results.

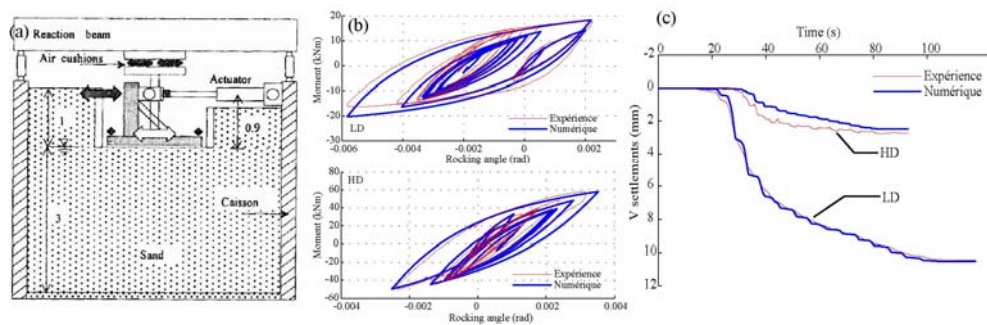


Figure 4. Tests TRISEE, moment-rotations and time history of the vertical settlements for the High density (HD) and the Low density sand (LD).

Dynamic behaviour

The simulation of the CAMUS IV experiment [2] performed on the seismic table of CEA Saclay is presented hereafter in order to evaluate the efficiency of the macro-element to predict the behaviour of a slender structure submitted to a dynamic loading. The mock-up represents a 5 storey building on a 1/3 scale. The structure is submitted to the earthquake motion Nice 0,33g.

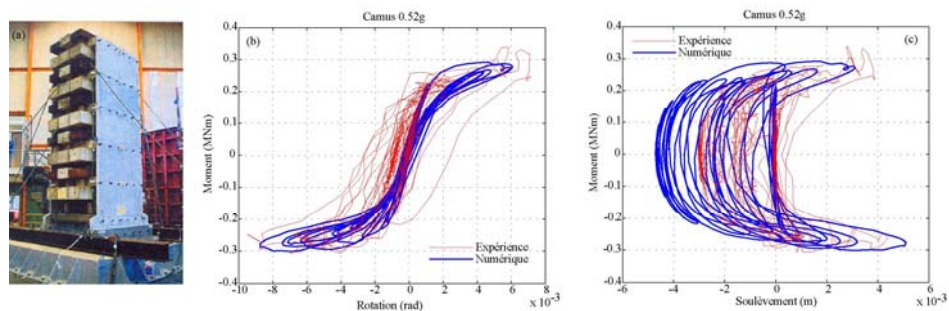


Figure 5. Test CAMUS IV, moment-rotation and moment-uplift curves for Nice 0.52g.

The main trends of the behaviour of the structure are quite well predicted (figure 5): experimental and numerical curves are relatively in phase and the maximum values of the moment at the base are well reproduced.

Conclusions

The 3D macro-element developed within this work gives satisfactory results for simulating the non linear behaviour of shallow rigid foundations lying on an infinite space submitted to a monotonic static, cyclic or dynamic loading. Using global variables it presents the advantage of inducing low computational costs.

All the results presented in this paper are for loadings in a plane (2D). The calculation takes only a couple of minutes for each simulation. The 3D behaviour of the element has not been presented due to the difficulty to find experimental results with loadings in 2 horizontal directions. This point should constitute a future validation for the element.

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