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Simple 3D modelling of soil-pile-structure interaction for a group of energetic piles

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ABSTRACT: Energetic piles are pile foundations combined with heat pump; they are used as energy source for heating or cooling needs of buildings. Energetic piles provoke temperature variations inducing displacements and solicitations for the above structure. In this article, soil-pile-structure interaction model is proposed for a group of energetic piles, this model evaluate solicitations and displacements due to thermal loads. In this model, piles are represented by Hooke model, soil-pile interaction by a “t-z” model and structure by a rigidity matrix. Simulations based on Sept-Sorts case (France), an experimental project of a water-treatment plant founded on energetic piles, were conducted. Thanks to these calculations, this model allows to take into account structural effects, compared with simpler models for which the structure is only characterized by a specific rigidity at the upper part of the pile. Nevertheless, rigidity matrix is hard to compute, for some cases, structure model can be simplified. If all piles of a building are under the same thermal load, structure will globally move up without additional solicitation (due to thermal loads), a simpler model with free pile heads is sufficient.

RESUME : Les pieux géothermiques sont des fondations profondes équipées de pompes à chaleur. Ces pieux sont utilisés comme source d’énergie pour le chauffage ou le refroidissement des bâtiments. Les pieux géothermiques sont soumis à des variations de températures provoquant des tassements et des sollicitations dans la structure. Cet article présente une modélisation de l’interaction sol-pieu-structure pour un groupe de pieux géothermiques. Ce modèle calcule les sollicitations et les déplacements dus à un chargement thermique. Dans ce modèle, les pieux sont modélisés par la loi de Hooke, l’interaction sol-structure par la loi de Frank et Zhao (1982) et la structure est représentée par une matrice de rigidité. Ce modèle a été appliqué au cas de Sept-Sorts (France), un projet de station d’épuration sur pieux géothermiques. A la suite de ces calculs, plusieurs remarques sont faites. Ce modèle permet de prendre en compte des effets structurels (rigidité latérale de la structure et réaction des pieux non géothermiques) qui ne peuvent être traduits dans des modélisations plus simples. Le cas d’un bâtiment où tous les pieux subissent le même chargement thermique peut être simplifié en un modèle où les pieux sont libres en tête.

1 INTRODUCTION

Energetic piles consist of pile foundations combined with closed-loop ground source heat pump. Their purpose is to provide an alternative energy source for heating and cooling needs of buildings.

Energetic pile systems connected to structures require consideration of the complex interaction between temperature change and induced stresses or deformations. A cooled pile generates tensile strength whereas a heated pile generates compressive forces. Depending on fixity conditions of the piles and structure rigidity, these forces are redistributed between the soil and the structure. These interactions may affect building performance, modifying loading distribution and generating differential displacements.

2 SOIL-PILE-STRUCTURE INTERACTION

2.1 Energetic pile model

In this paper, the effects of thermal loads involving geothermal piles groups and structure are studied. A semi-analytical model, representing the overall behaviour is established. This model is adapted from TasPie+ software developed by TERRASOL simulating a pile under axial mechanical load.

Pile is represented by a Hooke model including thermal effects as following:

$$\frac{d(u-u_0)}{dx} = -\frac{N-N_0}{ES} + \alpha(T-T_0) \qquad (1)$$

Where phase “0” corresponds to pile state before applying thermal loadings:

- u: pile settlement (m);
- N: pile axial force (KN);
- ES: axial rigidity (KN);
- T: pile temperature (°K);
- α: thermal expansion factor ($°K^{-1}$).

2.2 Soil-pile interaction model

Interaction between soil and pile is divided in 2 parts:

- On pile shaft, mobilized shear stress (τ) is represented by a “t-z” model accounting for loading and unloading (Figure 1.) resulting in the following equation (where P is pile perimeter) :

$$\frac{dN}{dx} = -P\ \tau(u) \tag{2}$$

- Stress (σ_p) at pile base is also represented by the same “t-z” model with loading and unloading, except that only compressive strength is mobilized (Figure 2.). Pile base must follow this condition (where S is pile section area and L is pile length):

$$N(z = L) = N_p = S\ \sigma_p(u) \tag{3}$$

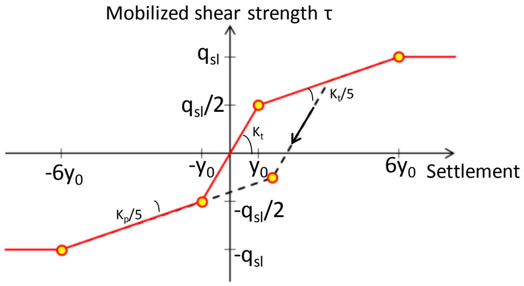

Figure 1. Mobilized shear strength model with unloading.

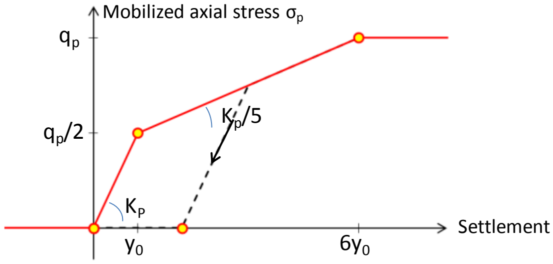

Figure 2. Mobilized axial stress model with unloading.

2.3 Structure model

In this model, two phases are calculated:

- A mechanical phase where mechanical loads imposed at pile head (phase “0”).
- A thermal phase where structure is modelled as a rigidity at pile head (Spring model and Rigidity matrix model)

2.3.1 Spring model

Structure can be modelled in thermal phase as a spring with rigidity “k” at pile head:

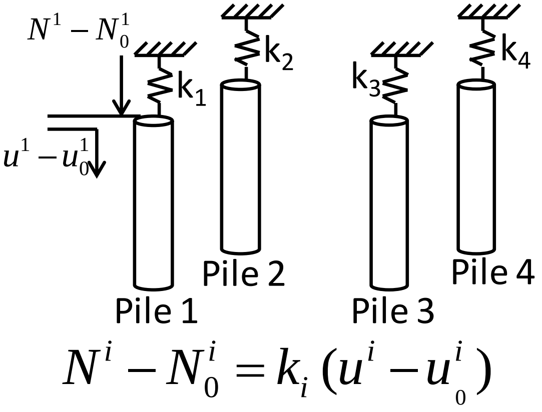

Figure 3. Spring model

This spring model does not take into account a group of piles (pile behaviours are independent from each other). To simulate a rigid structure (no settlement at pile head), a high rigidity should be chosen. To simulate a free head pile (no axial force on head), a rigidity equal to zero can be taken.

This simple model can be enough to simulate isolated piles behaviour. For a building on several piles, a rigidity matrix is introduced.

2.3.2 Rigidity matrix model

In civil engineering, structures are designed to be operative in elastic state. Therefore, in a structure, a linear relation can be found between foundation displacement and foundation vertical solicitation. This relation is noted as following:

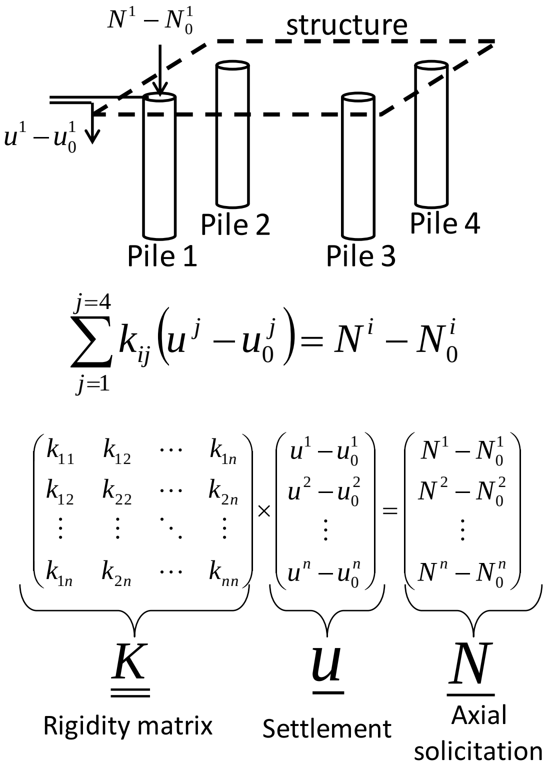

Figure 4. Rigidity matrix model

2.4 Solution

Equations (1) and (2) leads to a global matrix system where piles are discretised in finite elements of beam.

Given the elastoplastic behaviour of pile-soil interaction, resolution of the system requires an iterative analysis until convergence.

3 CASE STUDY

In this paper, the soil-structure-pile interaction model is used on an experimental project of a water-treatment plant founded on energetic piles (Sept-Sorts, France, Figure 5.).

The studied building is founded on 102 piles (length 11m, diameter 420 mm). These piles are anchored between 0.5m and 1m in the rock substratum of limestone. Out of these 102 piles, an half (48 piles) are energetic piles corresponding to the three upper rows of piles (see Figure 6.).

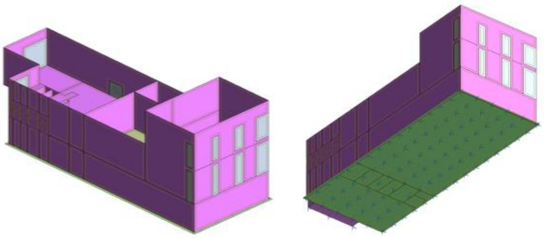

Figure 5. Sept-Sorts building design.

Solicitations and settlements will be examined on two cross sections, a “rigid section” corresponding to piles located under several concrete walls and a “flexible section” corresponding to piles located only under raft (Figure 6.).

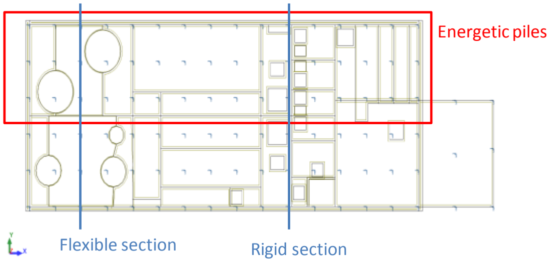

Figure 6. Sept-Sorts 102 piles, 48 energetic piles.

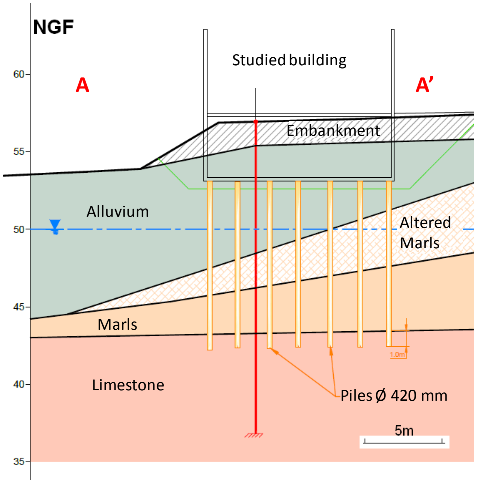

Figure 7. Sept-Sorts, soil cross section.

4 RESULTS

4.1 Models computed

Four structure models have been simulated:

- Structure represented by a rigidity matrix generated by the company PINTO (“Matrix structure model”). This structure model is the main model and will be compared to other simplified representations;
- Structure represented by spring at each pile head, rigidity of these springs is chosen equal to rigidity matrix diagonal (“Spring structure model”);
- Blocked pile heads (“Rigid structure model”);
- Free pile heads (“Flexible structure model”).

Two situations are studied

- Situation 1: 3 rows of piles are equipped as energetic piles (Figure 6.).
- Situation 2: All piles of the structure are energetic piles.

On these energetic piles, a cycle thermal load is applied (from T-T$_0$ = +20 °C to T-T$_0$ = -20 °C) results are shown after that 4 thermal cycles have been applied. The following graph presents head pile displacement of situation 1, where structure is represented by a rigidity matrix, on the rigid section, after a heating phase:

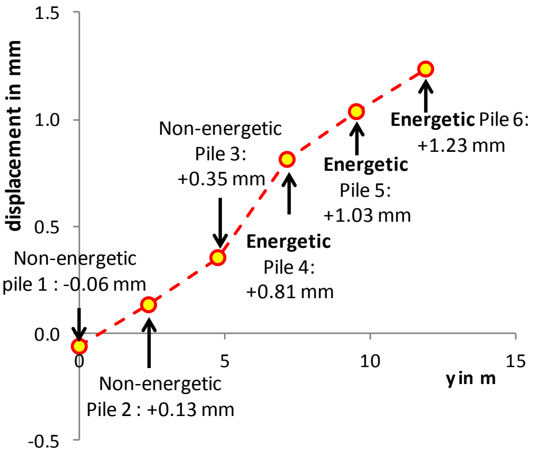

Figure 8. Displacement in rigid section due to heating

4.2 Situation 1

The figures below shows displacements and solicitations at pile heads due to thermal cycles for the four structural models, for a “partial” set of energetic piles in the cross section for T-T$_0$ = +20 °C.

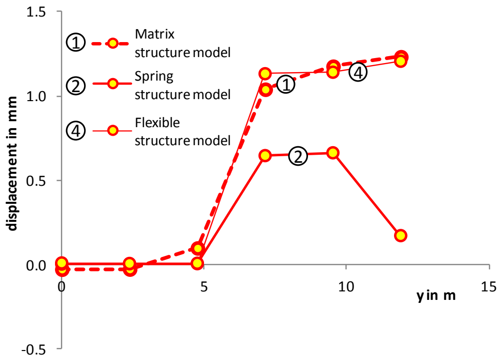

Figure 9. Structure vertical displacement (flexible section) due to cycle thermal loads.

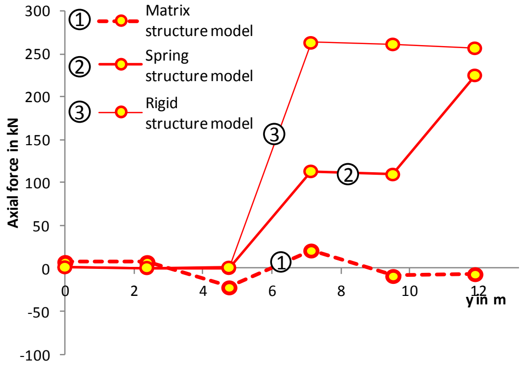

Figure 10. Axial force in structure (flexible section) due to cycle thermal loads.

Model using rigidity matrix is compared to other models. Model using a rigid raft is overestimating thermal force, in both sections (rigid and flexible). Model using infinitely flexible is the model which gives the best settlement estimation, in the flexible section.

Even in the rigid section, flexible structure model and matrix structure model gives settlement of comparable order. In flexible structure model (spring and rigid too), pile behaviours are independent from each other whereas in matrix structure model, rigidity matrix make pile head behaviour dependant from each other. Only, the rigidity matrix adds to the model the structural complex behaviour which is really visible on the rigid section.

In the rigid section, structure raft is uplifting due to thermal dilatation of 3 rows of energetic piles. As this section is rigid, not only raft over thermal loaded piles moves but raft over the non loaded piles follows it. Finally, under this asymmetrical load, structure in this section is behaving like a rigid solid, the structure rotates but do not bend. Only the rigidity matrix model can represent this lateral rigidity while other model can only simulate vertical rigidity (Figure 9.).

The whole structure is founded on piles, all loads from structure goes through piles and not directly through soil. All mechanical loads transmitted to the structure due to thermal loads must be compensated on other piles. Consequently, the sum of load increment, induced by thermal loads, on all piles head (energetic and normal piles) should be equal to 0:

$$\sum_{i=1}^{i=n}(N^i - N_0^i) = 0$$

With the rigidity matrix structure model, this condition is respected, while heated piles are globally compressed, normal piles as compensation are in traction (Figure 12.). In others models each pile are independent from each other, no solicitation exists in normal piles (no traction), load transmission through structure is not modelled.

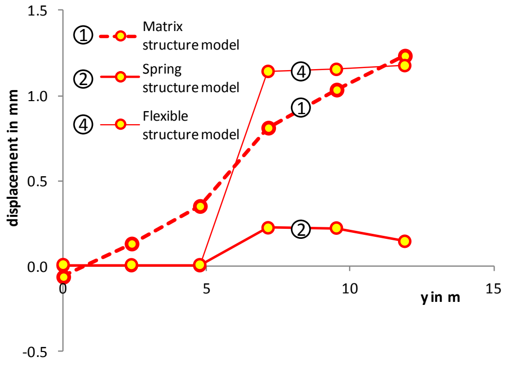

Figure 11. Structure vertical displacement (rigid section) due to heating.

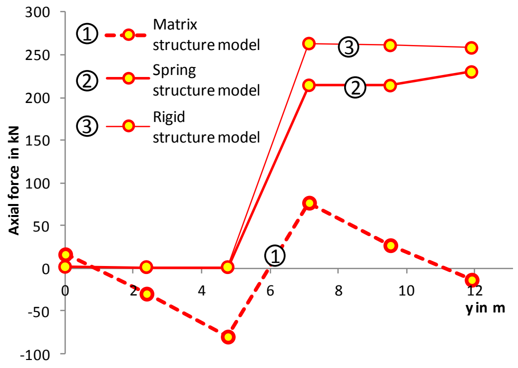

Figure 12. Axial force in structure (rigid section) due to heating.

Table 1. Extreme solicitations and extreme displacements in rigid section due to heating ("Partial energetic model")

Model	Maximal displacement	Minimal displacement	Maximal solicitation	Minimal solicitation
Matrix model	1.2 mm	-0.1 mm	77 kN	-80 kN
Spring model	0.2 mm	0 mm	230 kN	0 kN
Rigid model	0 mm	0 mm	263 kN	0 kN
Flexible model	1.2 mm	0 mm	0 kN	0 kN

4.3 Situation 2

In this model, the same thermal load as before is applied to all piles and not just half of them. In the flexible section where structural deformation is likely to happen, solicitations and displacement of pile head is observed (Figure 13., Figure 14. and Table 2.).

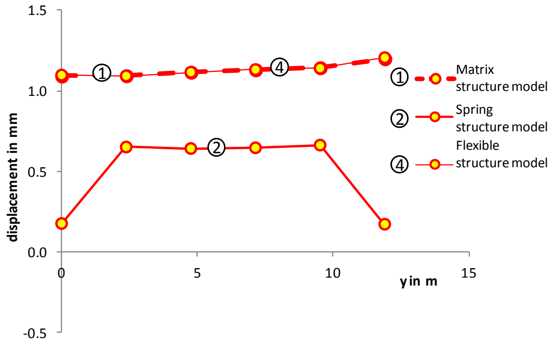

Figure 13. Structure vertical displacement (flexible section) due to thermal load in all piles.

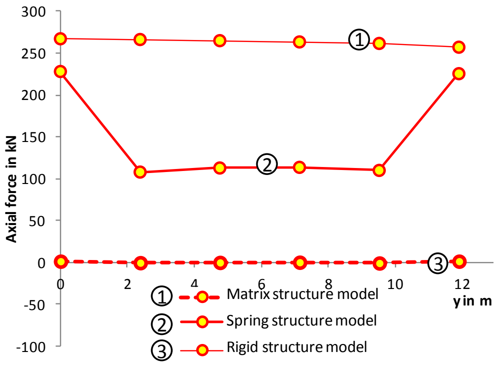

Figure 14. Axial force in structure (flexible section) due to thermal load in all piles.

Table 2. Extreme solicitations and extreme displacements in flexible section due to heating ("Fully energetic model")

Model	Maximal displacement	Minimal displacement	Maximal solicitation	Minimal solicitation
Matrix model	1.2 mm	1.1 mm	2 kN	-1 kN
Spring model	0.7 mm	0.2 mm	228 kN	108 kN
Rigid model	0 mm	0 mm	267 kN	257 kN
Flexible model	1.2 mm	1.1 mm	0 kN	0 kN

Model using rigidity matrix is compared to other models. This model in this case gives results similar to the flexible structure model for displacements and for solicitations (when compared to rigid structure model or spring structure model, solicitations in matrix structure model are really low).

As mentioned before, all piles are under the same thermal load, and then solicitations at their head should be approximately the same and the sum of all solicitations due to thermal loads should be equal to 0. Then all these solicitations are equal to 0. That's why, in this model, thermal load on all piles provoke a global uplifting of the structure as a rigid solid, but do not provoke additional load. This phenomenon can be understood for the hypothetical case of a structure founded on only one pile, solicitation in pile is only equal to the global mechanical and is independent from pile temperature.

Based on these results, a model where pile head are free to move (flexible structure model) can be a relatively accurate model in case of a building fully equipped by energetic piles.

5 CONCLUSION

A model of soil-pile-structure interaction has been developed for energetic pile group. This model represent pile behaviour using Hooke model, pile-soil interaction is based on "t-z" model and structure-pile behaviour is represented by a rigidity matrix. This model can simulate structural effects such as traction in non energetic piles and lateral rigidity which cannot appear in simpler models where structure model is only a spring.

This soil-pile-structure model can be simplified. When all structure piles are under the same thermal load, a soil-pile interaction model with free pile head can be used. In this specific case, rigidity matrix does not need to be computed.

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