Influence of micropile inclination on the performance of a micropile network

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Micropiles are defined as small-diameter, drilled and grouted piles. They are used in groups for underpinning existing structures and as a foundation support for new structures. They can also be used in networks as a technology of ground improvement. In this case, both vertical and inclined micropiles are utilised to create a geocomposite material with both high stiffness and resistance. This paper aims at analysing the performances of a micropile network implemented in a wall configuration. The first part of the paper describes the numerical model used for the analysis of this network, and the second and third parts analyse the performance of the micropile network under lateral and vertical loads. Analysis shows that the inclination of micropiles results in an improvement of both the stiffness and the bearing capacity of the micropile network.

Keywords: bearing capacity; finite element; inclination; lateral; micropiles; network; stiffness; vertical

Les micropiles sont définies comme étant des piles de petit diamètre, forées et cimentées. Elles sont utilisées par groupes pour soutenir les structures existantes et comme support de fondation pour les nouvelles structures. Elles peuvent aussi être utilisées en réseau, comme technologie d'amélioration des sols. Dans ce cas, des micropiles verticales et inclinées sont utilisées pour créer un matériau géocomposite ayant à la fois une forte rigidité et une haute résistance. Cet exposé a pour but d'analyser les performances d'un réseau de micropiles implanté dans une configuration de mur. La première partie décrit le modèle numérique utilisé pour l'analyse de ce réseau ; les seconde et troisième parties analysent la performance du réseau de micropile sous charges verticales et latérales. L'analyse montre que l'inclinaison des micropiles donne une amélioration de la rigidité et de la résistance mais aussi de la capacité porteuse du réseau de piles.

Introduction

Micropiles are defined as small-diameter, drilled and grouted piles. They were first used in Italy in the 1950s to underpin historic buildings; their use was then broadened as a foundation support for new constructions and for underpinning existing structures, particularly in difficult access areas (Lizzi, 1978, 1982). Micropiles can be used in virtually every ground condition with minimal disturbance of the soil or the surrounding structures.

Micropiles can also be utilised for ground reinforcement (Bruce et al., 1997; Schlosser and Frank, 2004). In this case, both vertical and inclined micropiles are used to create a geocomposite material with both high stiffness and resistance. The resulting soil improvement is due to the increase in frictional resistance between the micropiles and the soil, and to the network effect. The concept of the micropile network consists in the creation of a confined soil–micropile composite structure that can work for underpinning, stabilisation and earth retention. Tests conducted by Lizzi (1982) showed that the use of micropiles in a network configuration resulted in a positive 'network effect' in terms of stiffness. Centrifuge and calibration chamber tests conducted by the French project FOREVER (Schlosser and Frank, 2004) showed that the micropile network presents a positive effect, although this is less important than that observed by Lizzi.

There has been little work on the numerical analysis of micropile networks, because of the difficulties encountered in the three-dimensional numerical modelling of a soil mass reinforced by a high number of micropiles with different inclinations (Shahrour, 2003). Recent achievements in the numerical modelling of geocomposites by the formulation of a three-dimensional embedded beam element allow the use of the finite-element method for analysing the performance of geocomposite structures such as micropile networks (Sadek, 2003; Sadek and Shahrour, 2004). In this paper, this element is used for analysing the behaviour of a micropile network resulting from the implementation in the soil mass of successive groups of micropiles (Fig. 1). Each group is composed of two parallel rows of micropiles with opposite inclinations. The first part of this paper describes the numerical model used for the analysis of this network, and the second and third parts analyse the performance of this network under lateral and vertical loads.

Numerical model of micropile network

The micropile network under consideration concerns ground improvement by a wall of micropile–soil composite, as illustrated in Fig. 1. It consists in the reinforcement of a soil mass by successive groups of micropiles. Each group is composed of two rows of micropiles with opposite

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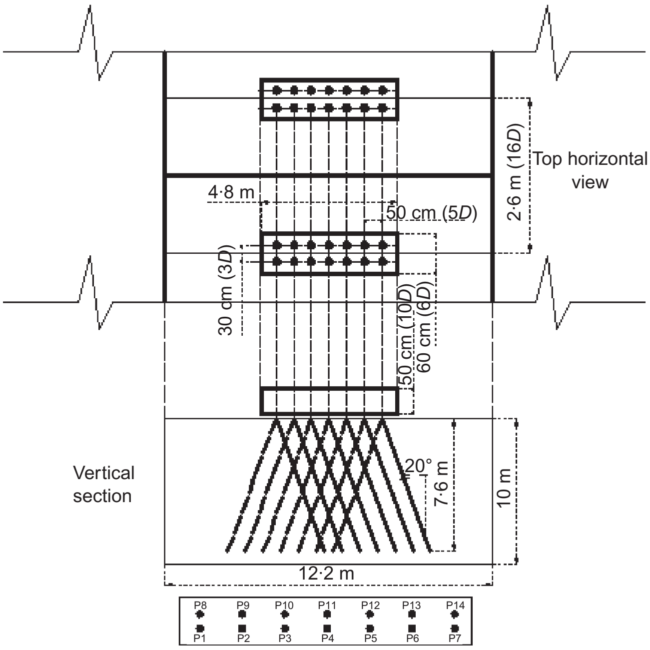


Fig. 1. Network in a wall configuration

inclinations. The micropile diameter, D_p, is 0·1 m, and the axial and bending stiffness are equal to $EA_p = 141$ MN and $EI_p = 36$ kN m^2 respectively. The spacing between the two rows is equal to $3D_p$. The number of micropiles in the group, N_p, is 14, which means that each row is composed of seven micropiles. The distance between the groups of micropiles is equal to $10D_p$.

Thanks to the symmetry of the network, the finite-element analysis is conducted for a group of micropiles as illustrated in Fig. 2. The reinforced soil section is $26D_p$ wide, 10 m deep and 12·2 m long. The soil behaviour is assumed to be linear elastic, with Young's modulus $E_s = 50$ MPa and Poisson's ratio $\nu_s = 0{\cdot}45$. Joint elements are used to model the contact between the soil and the micropiles. These elements allow slipping between the soil and the micropiles. The interface is assumed to be purely cohesive with a resistance to friction $C_t = 60$ kPa and a tangential stiffness $K_t = 25$ MPa.

Finite-element analyses were carried out using the finite-element program PECPLAS (Sadek, 2003; Sadek and Shahrour, 2004). This program provides interesting facilities for modelling the soil reinforcement, and in particular the possibility to use the 'embedded beam element', which allows the use in the finite-element model of beam elements that can deviate from the nodes of the solid elements. Analyses were conducted using the finite-element mesh illustrated in Fig. 2, which includes 7008 cubic elements.

The following sections present successively the results obtained for lateral and vertical loadings. For each load, a reference case is first presented, and then the influence of micropile inclination on the performance of the micropile network is analysed.

Micropile network under lateral loading

Reference case

The reference case concerns the micropile network illustrated in Fig. 1. This network is composed of micropiles

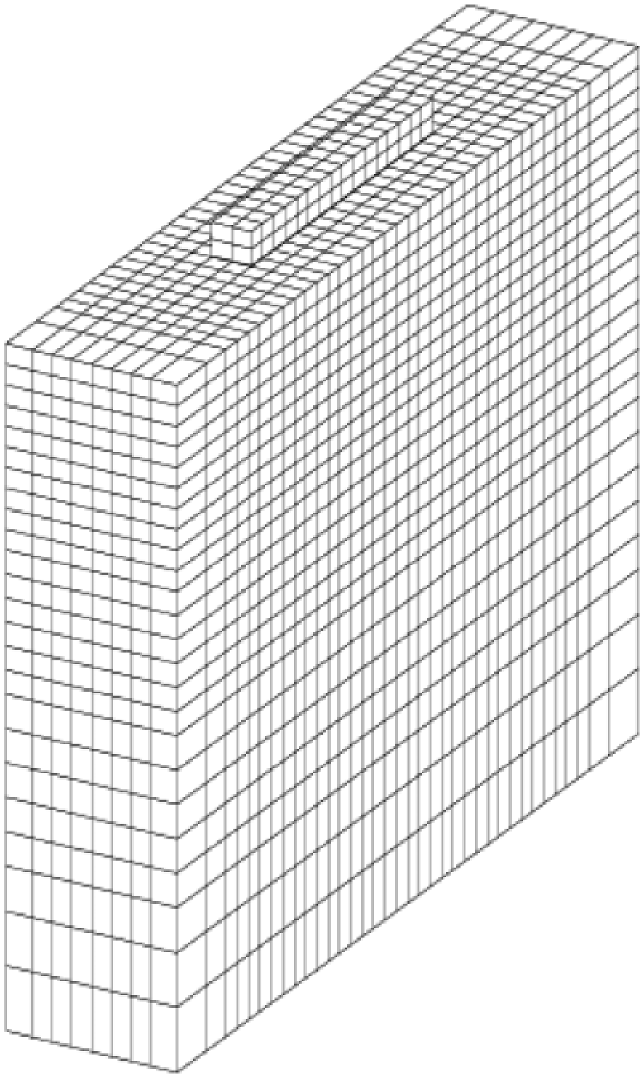


Fig. 2. 3D mesh used in the finite-element analysis of the network

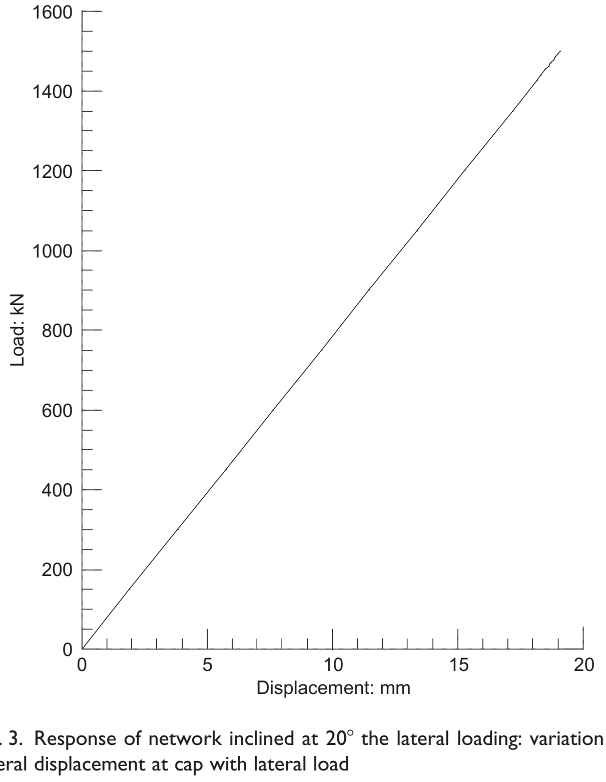
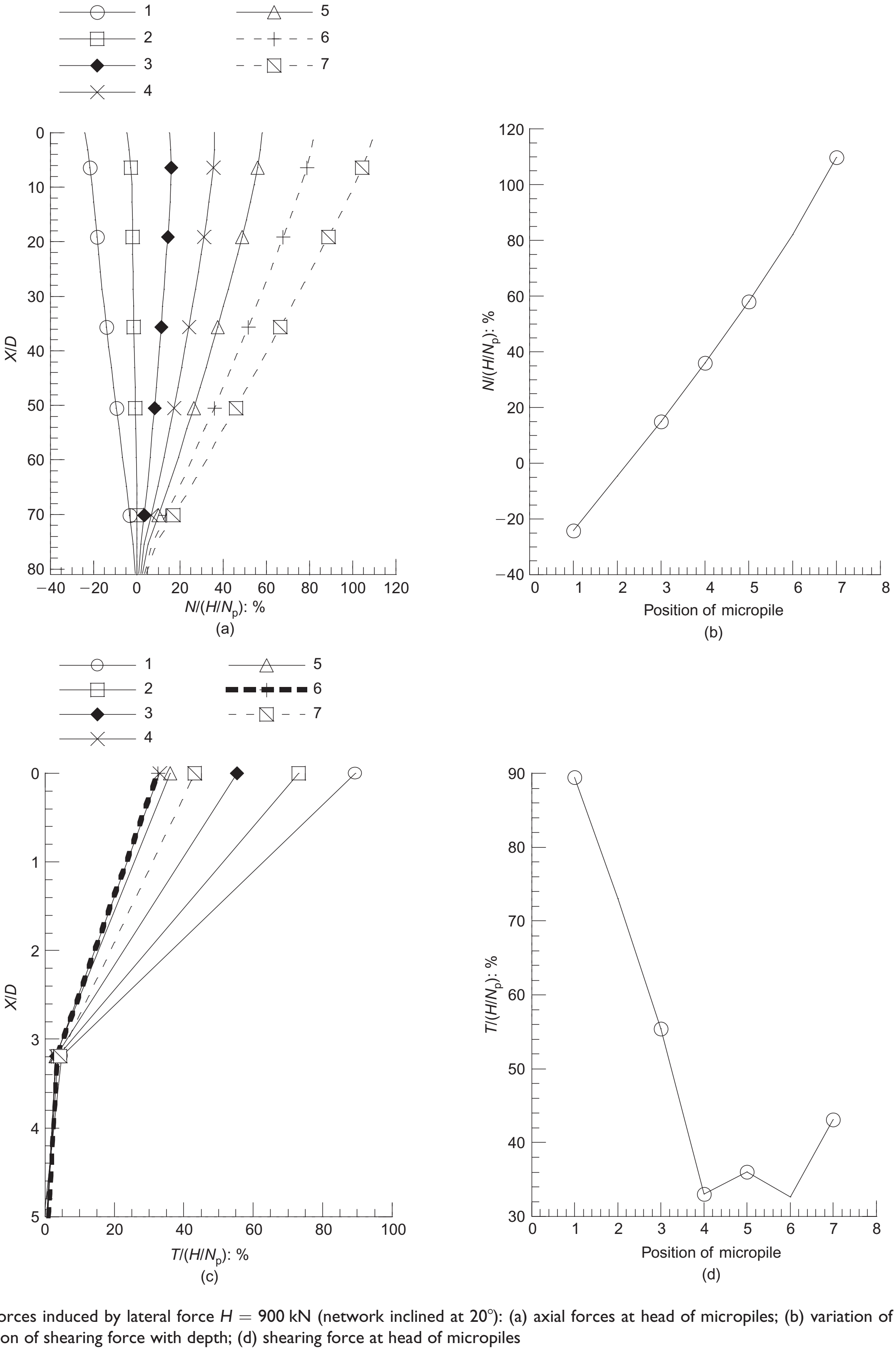


Fig. 3. Response of network inclined at 20° the lateral loading: variation of lateral displacement at cap with lateral load

inclined at 20° to the vertical and submitted to a lateral load H.

The response of this network to the lateral load is depicted in Fig. 3. It can be seen that the lateral force induces a lateral displacement at the cap, which increases linearly with the force up to $H = 1500$ kN. The corresponding lateral displacement u_h is 19 mm. The lateral stiffness of the network R_h ($= H/u_h$) is 79 MN/m.

The distribution of the axial force in the micropiles is shown in Fig. 4(a) for the lateral load $H = 900$ kN. Because of symmetry, the results obtained for the micropiles in the first row (piles 1 to 7) are equal to those induced in the micropiles of the second row (8 to 14). It can be seen that the lateral load causes compression forces in the front micropiles and extension in the rear micropiles. The compressive forces increase when going from the centre of the group to the front micropiles. The maximum axial force in the front micropile is equal to 110% of the mean lateral load H/N_p, and the tension in the rear micropile is equal to 25% of H/N_p.



(a)

(b)

(c)

(d)

Fig. 4. Internal forces induced by lateral force $H = 900$ kN (network inclined at 20°): (a) axial forces at head of micropiles; (b) variation of axial force with depth; (c) variation of shearing force with depth; (d) shearing force at head of micropiles

Figure 4(c) depicts the variation of the shearing force in the micropiles. The maximum shearing force is induced in the rear micropile. The shearing force decreases when going from the rear micropile towards the centre of the group and then increases when going towards the front micropile. The maximum shearing force at the head of the rear micropile is equal to 90% of H/N_p, whereas it is equal to 32% of H/N_p in micropiles 4 and 5. It can be observed that the sum of the shearing forces at the head of the micropiles is about 48% of the lateral load, which means that 52% of the load is sustained by the axial component of the micropiles.

Influence of inclination

Numerical simulations were conducted for vertical micropiles and for micropiles inclined at 20° and 30° to the vertical. Fig. 5 depicts the influence of micropile inclination on the response of the micropile network to lateral load. It clearly shows that inclination of the micropiles has a beneficial effect on their performances. It leads to an increase in the lateral stiffness of the network. Indeed, the lateral stiffness of the network inclined at 30° is about 25% higher than that with vertical micropiles.

Figures 5(b)–(d) show the distribution of the internal forces at the head of the micropiles for lateral load $H =$

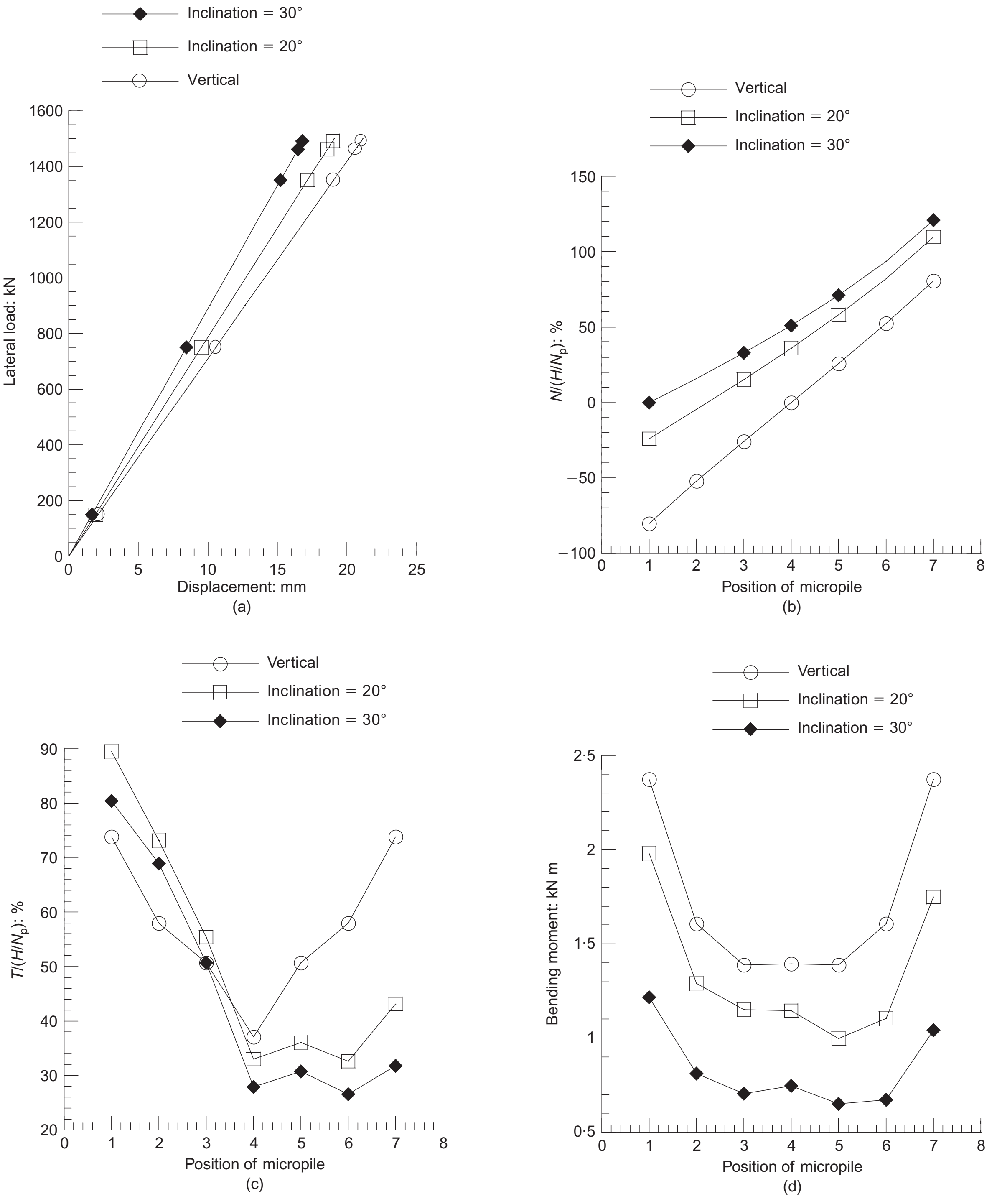


Fig. 5 Influence of inclination of micropiles on response to lateral load: (a) variation of lateral displacement at cap; (b) axial forces at head of micropiles; (c) shearing forces at head of micropiles; (d) bending moment at head of micropiles

900 kN. The axial force at the head of the vertical micropiles shows an antisymmetric distribution. An increase in the inclination of micropiles results in an increase in the compression forces in the front micropiles and a decrease of the tension forces in the rear micropiles. The axial force in the front micropile for the network inclined at 30° is about 50% higher than that in the vertical group. The total of the axial forces at the head of the micropiles in the network inclined at 30° to the vertical is equal to 54% of the applied lateral load *H*. This result indicates that inclination of the micropiles improves the mobilisation of the axial component of the micropiles, which results in an increase in the lateral stiffness of the micropile network.

The inclination has also a positive effect on the shearing forces. It leads to a significant reduction in the shearing forces in the front micropiles. Indeed, the shearing force in the front network inclined at 30° is about 43% of that induced in the vertical group. The influence of inclination on the shearing force of the rear micropiles is less significant. Inclination of the micropiles also leads to a significant decrease in the bending moment: the maximum bending moment in the network inclined at 30° is about 50% of that induced in the group of vertical micropiles (Fig. 5(d)).

Influence of micropile rigidity

Simulations were conducted for a network with stiffer micropiles ($EA_p = 1100$ MN and $EI_p = 850$ kN m^2) compared

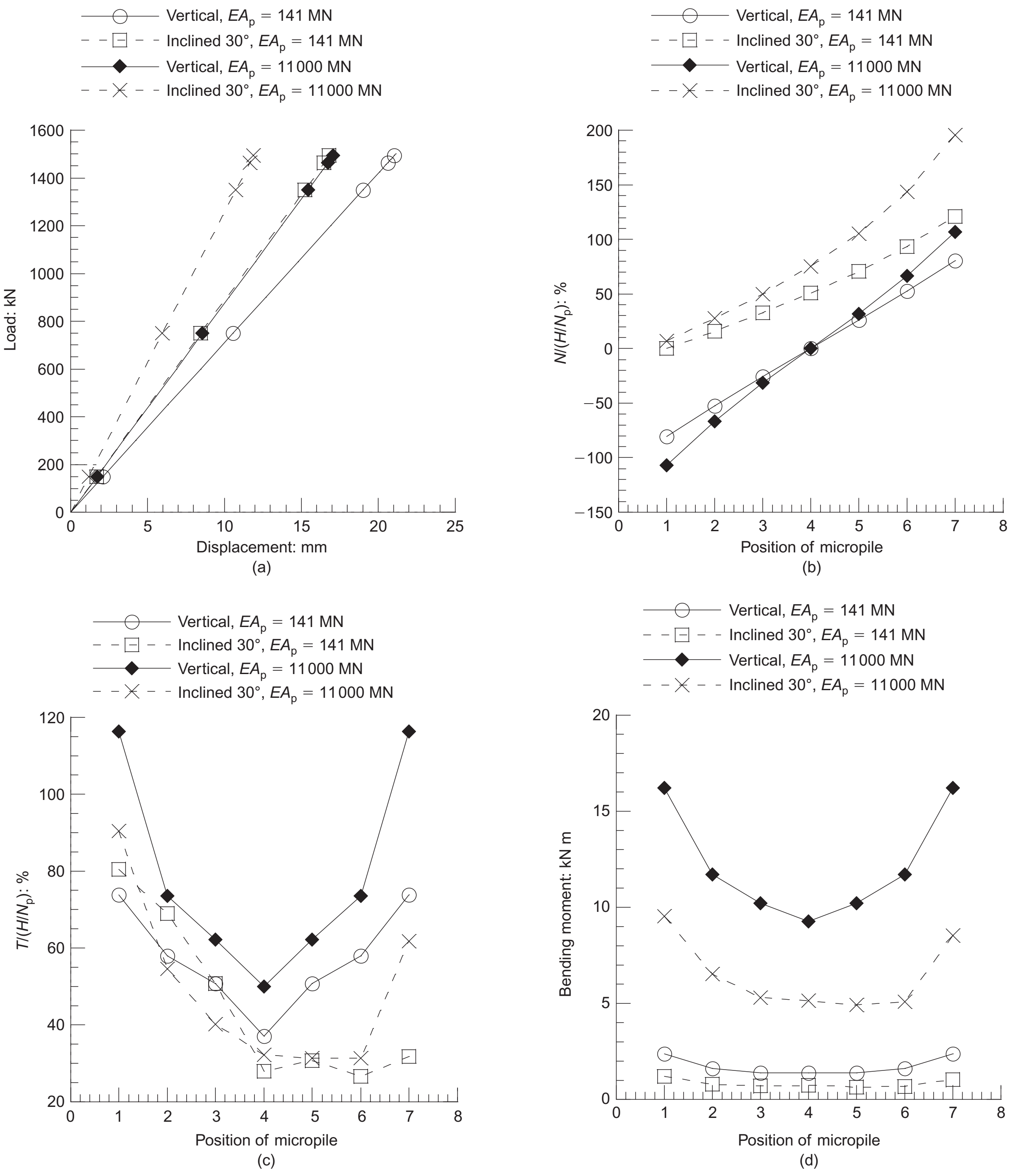


Fig. 6. Influence of inclination of micropiles on response to lateral load: (a) variation of lateral displacement at cap; (b) axial forces at head of micropiles; (c) shearing forces at head of micropiles; (d) bending moment at head of micropiles

with the micropiles used in the reference case ($EA_p = 141$ MN and $EI_p = 36$ kN m^2). The results of these simulations are given in Figs 6(a)–(d). It can be seen that the rigidity of the micropiles is a key parameter for the performance of the micropile network under lateral loading. For the vertical network, the lateral stiffness with the stiffer micropiles is about 25% higher than that with flexible micropiles, and for the network inclined at 30° the same increase in micropile stiffness leads to an increase of about 43% in the lateral stiffness of the network (Table 1). The increase in micropile stiffness also leads to an important increase in the axial forces in the micropiles (Table 2), which attains 60% for inclined micropiles. It also results in a significant increase in the shearing forces in the micropiles, particularly for vertical micropiles (Table 3). The stiffness of the micropiles also significantly affects the bending moment: the maximum bending moment in the network with stiff micropiles is about seven to eight times that induced in the network with flexible micropiles.

Vertical loading

Reference case

The response of the network inclined at 20° to the vertical loading is depicted in Fig. 7. It can be seen that the vertical displacement at the cap at first increases linearly with the force up to $V = 2100$ kN; then a decrease in the network stiffness is observed, which is due to slipping at the interface between the micropiles and the soil. The computation was carried out up to the limit value $V_{\text{lim}} = 2650$ kN. The vertical stiffness of the network in the linear part, R ($= V/u_v$), is 120 MN/m.

Figures 8(a)–(d) illustrate the distribution of the internal forces at the head of the micropiles for the vertical load $V = 1590$ kN. It can be seen that the maximum axial force is induced in micropile 7, which is inclined towards the exterior of the network. The axial force at the head of this micropile is equal to 95% of the mean vertical load V/N_p. The minimum axial force is induced at the network centre; it is equal to 82% of V/N_p. The distribution of the axial force at the micropiles is similar to that of the vertical stress under a rigid footing subjected to a vertical load.

The distribution of the shearing force in the micropiles shows an increase when going from the centre of the group towards the corner. The shearing force at the head of the centre micropile (micropile 4) is equal to 20% of V/N_p, whereas it is equal to 37% of V/N_p at the head of micropile 2. Vertical load induces a low bending moment in the micropiles (Sadek, 2003).

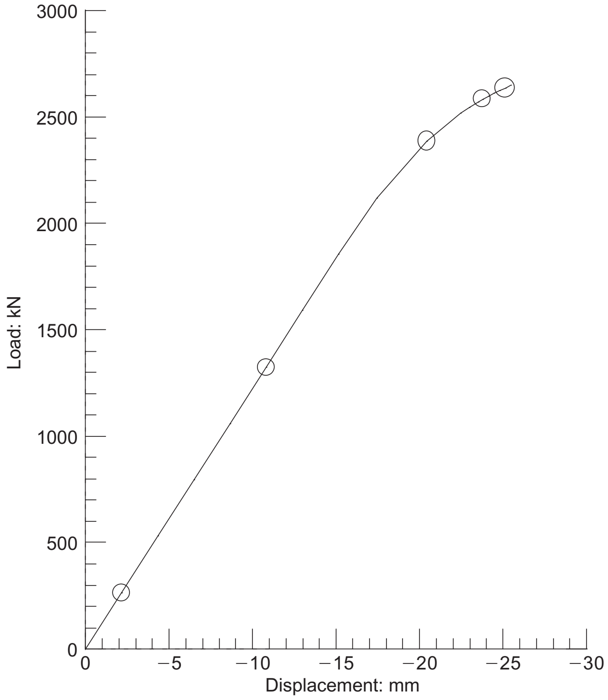


Fig. 7. Response of network inclined at 20° to vertical loading: variation of the vertical displacement at the cap with the vertical load

Table 1. Influence of inclination and rigidity of micropiles on horizontal rigidity of network

Inclination: degrees	0	20	30
Flexible network: MN/m	70	78	88
Rigid network: MN/m	88	105	126
Improvement: %	+26	+35	43

Table 2. Influence of inclination and rigidity of micropiles on normal force at head of micropile network ($\Sigma N_t/F_{\text{applied}}$)

Inclination: degrees	0	20	30
Flexible network: %	44	48	54
Rigid network: %	58	74	86
Increase: %	+32	+54	+60

Table 3. Influence of inclination and rigidity of micropiles on shear force at head of micropile network ($\Sigma T_t/F_{\text{applied}}$)

Inclination: degrees	0	20	30
Flexible network: %	57	52	45
Rigid network: %	79	62	48
Increase: %	+38	+19	+7

Influence of inclination

Figure 9 shows the influence of inclination of the micropiles on the performance of the network under vertical loading. It can be seen that the inclination of micropiles affects the initial stiffness very slightly, but it greatly increases the bearing capacity of the network. The bearing capacity of the network inclined at 30° is about 50% higher than that of the vertical network. The increase in bearing capacity of the network results from the beneficial effect of inclination in reducing the axial force in the micropiles, as shown in Fig. 9(b). The axial force at the head of micropile 1 in the network inclined at 30° is about 25% lower than that in the vertical network. The decrease in axial force with inclination is accompanied by an increase in shearing force. The shearing force at the head of micropile 2 increases from $0{\cdot}06F/N_p$ to $0{\cdot}38F/N_p$ when the inclination increases from 0° to 30°.

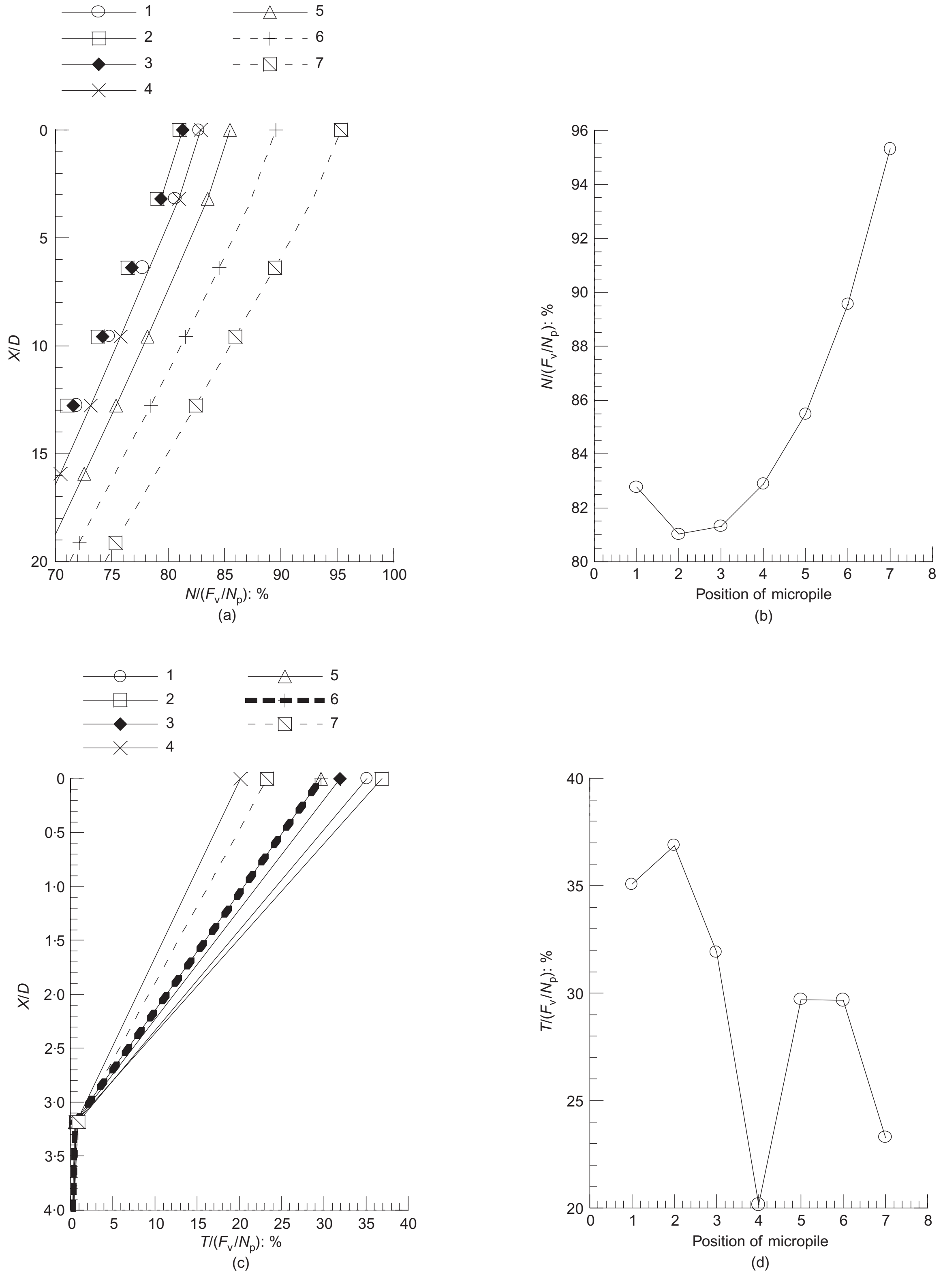


Fig. 8. Internal forces induced by vertical force $F_v = 1590$ kN (network inclined 20°): (a) variation of axial force with depth; (b) axial forces at head of micropiles; (c) variation of shearing force with depth; (d) shearing forces at head of micropiles

Conclusion

This paper included analysis of the performance of a micropile network in a wall configuration under both lateral and vertical loadings. Analysis shows that the use of inclined micropiles results in an improvement of the performance of the micropile network under both lateral and inclined loadings. Under lateral loading, inclination of the micropiles allows for good mobilisation of the axial stiffness of the micropiles and consequently results in an increase in the lateral stiffness of the network and a reduction of both the shearing forces and the bending moment in the micropiles. Under vertical loads, inclination of the micropiles results in a reduction of the axial forces and consequently in an increase in the bearing capacity of the network.

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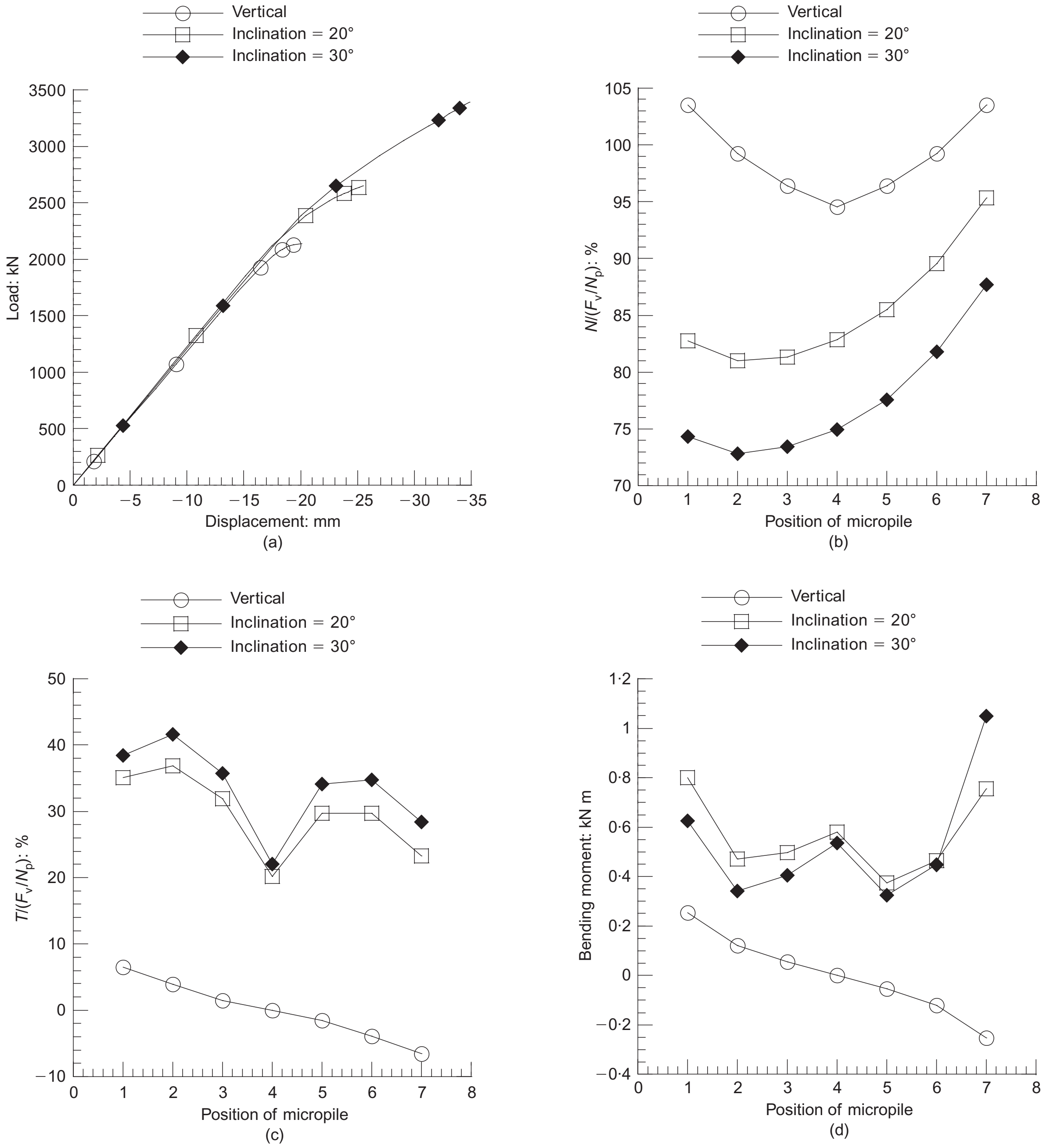

Fig. 9. Influence of inclination of micropiles on response to vertical load: (a) lateral displacement at cap; (b) axial forces at head of micropiles; (c) shearing forces at head of micropiles; (d) bending moment at head of micropiles

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Discussion contributions on this paper should reach the editor by 2 April 2007