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Compression mechanism of DMM pile in subsiding soft ground under embankment loading with application to bridge approach embankment

Mécanismes de compression de pieux DMM dans un sol mou s'affaissant sous une charge de remblai, applique à un remblai d'approche d'un pont

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ABSTRACT
A full scale deep mixing improved soft clay ground overlain by 6.0 m high reinforced embankment was constructed and monitored in order to study its deformation and consolidation characteristics. The local differential settlement between the deep mixing pile and its surrounding clay, which could induce downdrag skin friction, was observed from the full-scale test. The effect of local differential settlement and piezometric drawdown on the development of negative skin friction and the compression of the deep mixing piles are discussed, and an analytical method for long-term settlement analysis is presented. To avoid consequent undulation of the pavement at bridge approach, it is crucial that the lengths of deep mixing piles supporting the approach embankment must be varied smoothly. A method of proportioning the lengths and a typical layout of DMM piles for bridge approach embankment are presented.

RESUME
Un test grandeur nature sur un sol d'argile molle amélioré par un mixage profond et surmonte d'un remblai d'essai renforcé a été réalisé afin de mesurer et d'étudier ses propriétés de déformation et de consolidation. Il a été observe dans le test grandeur nature que l'affaissement différentiel local entre le pieu de mixage profond et l'argile qui l'entoure peut provoquer un frottement négatif. L'effet d'affaissement local différentiel et de gradient piézométrique sur le développement d'une pression négative et la compression des pieux de mixage profond sont discutés. Une méthode analytique d'affaissement à long terme est présentée. Pour éviter une ondulation à l'approche du pont, il est crucial que les longueurs des pieux de mixage profond soutenant le remblai d'approche varient progressivement. Une méthode de proportionnement des longueurs et un alignement typique des pieux de mixage profond pour l'approche d'un pont sont présentés.

1 INTRODUCTION

The Deep Mixing Method (DMM) has been recently applied to address the problem on differential settlement at bridge approaches on soft, subsiding ground which jeopardises the smooth transition between the bridge and the approaching highway embankment (e.g. Lin and Wong, 1999). Case histories revealed that the magnitude of the settlement of surrounding soil is always higher than that of DMM pile (Bergado et al., 1999; Bergado and Lorenzo, 2003). This unequal straining of DMM pile and its adjacent soil would induce downdrag (negative) skin friction on the DMM piles.

A full scale DMM-improved soft clay foundation supporting a 6m high reinforced embankment was constructed in Thailand and was monitored in order to study its consolidation and deformation characteristics. The compression and bearing mechanism of DMM pile under embankment loading, with and without piezometric drawdown, is illustrated and discussed in this paper. Finally, a simple method of proportioning the lengths of DMM piles for bridge approach embankment foundation is proposed.

2 REINFORCED TEST EMBANKMENT

2.1 Site and the Test Embankment

The Test Embankment, a six-meter high embankment reinforced with PVC-coated hexagonal wire mesh reinforcement, was constructed on DMM-improved soft clay deposit in Wangnoi District, Ayuthaya, Thailand. The foundation soils and their properties at the site of the test embankment are shown in Fig. 1 The foundation subsoil was first improved with soil-cement columns which were installed *in situ* by jet mixing method employing a jet pressure of 20 MPa. Soil-cement piles, with diameter and length of 0.5 m and 9.0 m, respectively, were installed at 1.5 m spacing in square pattern (Figs. 2a,b). The water-cement ratio (W/C) of the cement slurry was 1.5, and the cement content of the soil-cement pile was 150 kg/(m^3 of soil). The embankment was made of well-compacted silty-sand backfill reinforced with PVC-coated hexagonal wire mesh (Bergado and Lorenzo, 2003).

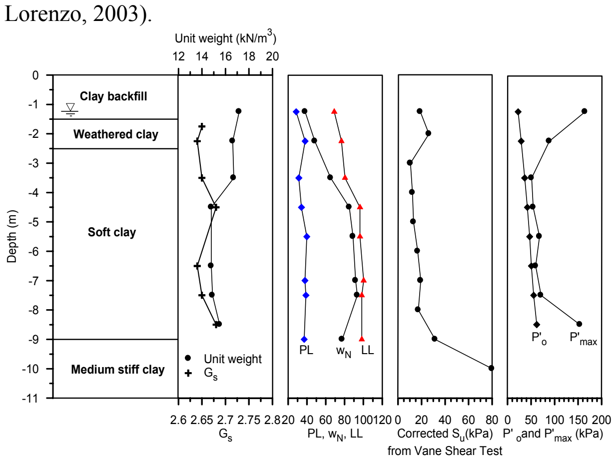


Figure 1. Soil profiles under the Test Embankment.

2.2 Construction and consolidation settlement

Figure 3 shows the settlements on top of deep mixing piles and on the surface of surrounding clay during and after construction up to one year of full embankment loading. The average settlements on deep mixing pile and on clay amounted to about 285 and 335 mm, respectively, one year after embankment construction. Using the method of Asaoka (1978), the maximum total settlements of deep mixing pile and of the surrounding soil from settlement plates S11 and S15 amounted to 340 and 440 mm, respectively. If there had been no improvement in the foundation soil, the settlement of embankment one year after construction could have been greater than 1000 mm (Bergado and Lorenzo, 2003). Thus, the embankment load (weight of embankment) has been transferred to the deep mixing piles, thereby not only reducing the intensity of pressure on the surrounding clay and the magnitude of its settlement, but also increasing the bearing capacity of the improved foundation.

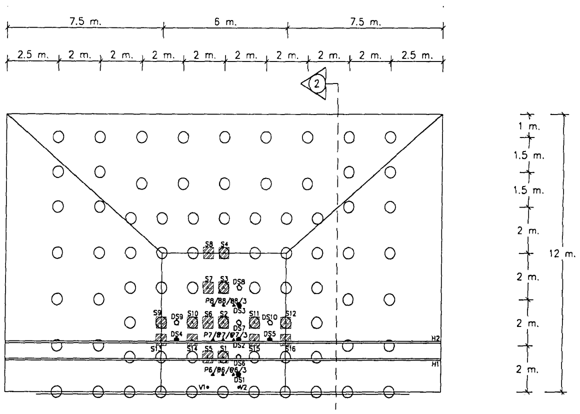


Figure 2a. Plan view of Test Embankment.

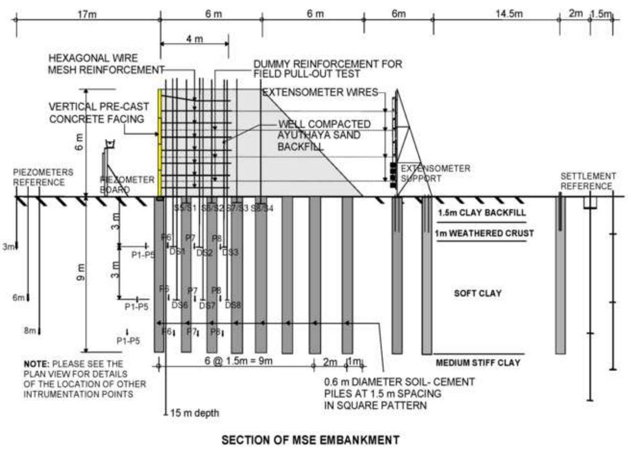


Figure 2b. Centerline elevation of Test Embankment.

2.3 Local differential settlement between deep mixing pile and surrounding clay

The local differential settlements between the pile and adjacent clay range from 25 mm to 60 mm (Figure 3) when the average settlement of deep mixing piles amounted to 285 mm after one year of full embankment loading. This implies that the local differential settlement between the deep mixing pile and the surrounding clay under the reinforced embankment could range from 8% to 20% of the average settlement. The local differential settlement between DMM pile and its surrounding clay could induce downdrag skin friction on the pile (Bergado et al., 2005). This local differential settlement, however, was almost eliminated at the surface of embankment due to the combined effect of compaction as well as reinforcement stiffness and arching of the overlying reinforced soil. Figure 3 also demonstrated that the magnitude of local differential settlements between piles and surrounding clay has been almost fully attained just after one month of full embankment loading. This practically implies that, for road embankment constructed on deep mixing piles, the final surfacing could be better done at least one month after embankment construction, giving time to compensate the differential settlement.

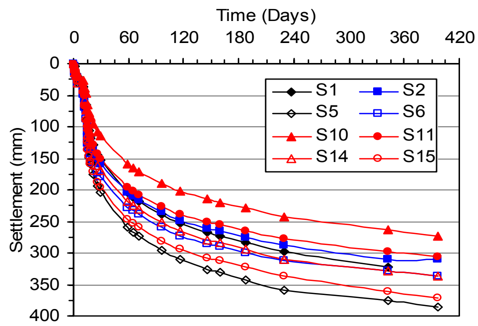


Figure 3. Surface settlement "on clay" and "on pile" (solid symbols=on piles; hollow symbols=on clay).

3 LONG-TERM SETTLEMENT OF DEEP MIXING PILE

3.1 Consolidation settlement - No piezometric drawdown

Figures 5a,b show the analytical model for the compression mechanism of single deep mixing pile in a unit cell of deep mixing improved ground as proposed by Lorenzo (2005). Figure 5a shows the compression mechanisms of deep mixing pile during consolidation, while Fig. 5b illustrates the mechanism of downdrag force induced by the local differential settlement between pile and the adjacent clay and by the piezometric drawdown. The following analyses are derived from the work of Lorenzo (2005) under the supervision of the first author.

The consolidation settlement due to the applied loading and the downdrag caused by the local differential settlement between the pile and adjacent clay, $\delta_{p,\sigma n}$, can be obtained as follows:

$$\delta_{p,\sigma n} = \left(\frac{C_{rp}}{1+e_{ot}}\right)(L_p)\mathrm{Log}\left[1+\frac{\Delta\sigma_p + 4\beta_{ave}\left(\frac{L_{neg}}{d_p}\right)(\sigma'_{vo,neg}+\Delta\sigma_s)}{\sigma'_{vop,ave}}\right] \quad (1)$$

$$\Delta\sigma_p = \frac{qm_r}{a(m_r)+(1-a)} \quad (2)$$

$$\Delta\sigma_s = \frac{q}{a(m_r)+(1-a)} \quad (3)$$

where $a=\left(\frac{d_p}{D_e}\right)^2$; $m_r=\left(\frac{E_{up}}{E_{us}}\right)$; q is the average applied loading; C_{rp} is the preyield compression index of the deep mixing pile; e_{ot} is the after-curing void ratio of the deep mixing pile; d_p is the diameter of deep mixing pile; D_e is the diameter of the equivalent tributary unit cell, which can be taken as 1.13S and 1.05S corresponding to square and triangular patterns, respectively, of deep mixing piles installed at 'S' spacing; $\sigma'_{vop,ave}$ is the average initial effective overburden pressure in the deep mixing pile, calculated considering no drawdown of hydrostatic pressure; $\sigma'_{vo,neg}$ is the initial average effective overburdened pressure in the adjacent surrounding soil over the length of the pile that is subjected to down-drag force only, L_{neg}, due to local differential settlement, and calculated considering no drawdown of hydrostatic pressure; β_{ave} is the average mobilized coefficient of downdrag skin friction over the length of deep mixing pile subjected to negative skin friction, L_{neg}; and E_{up} and E_{us} are the modulus of elasticity of DMM pile and surrounding soil, respectively. Equation (1) implicitly assumed that the actual stress shared on the deep mixing pile does not exceed its vertical yield stress, $\sigma_{v,y}$; otherwise, both the pre-yield and post yield compression must be determined.

3.2 Additional settlement due to the effect of piezometric drawdown

The piezometric drawdown causes reduction of the hydrostatic pressure which eventually gives an equivalent increase in the effective stress. Normally, the effective stress is calculated considering hydrostatic pressure condition only. Obviously, the presence of piezometric drawdown could lead someone to inadvertently underestimate the effective stress used in consolidation analysis and, hence, the downdrag force at the interface of deep mixing pile. Thus, the increment of effective stress due to drawdown is better calculated separately so that its effect on the compression of deep mixing pile can be evaluated properly. Two cases are described below to assess the effect of piezometric drawdown.

Case 1: Overestimation in the calculated consolidation settlement due to underestimation of initial overburden effective stress

The use of hydrostatic pressure for the calculation of pore water pressure would underestimate the initial overburden effective stress, if piezometric drawdown is actually present. Assuming the piezometric drawdown has already occurred for some time and the soil has already undergone the associated consolidation, then the underestimation of the initial overburden effective stress would result to overestimation of the consolidation settlement due to the applied loading. At the midheight of the portion of deep mixing pile that is subjected to piezometric drawdown (Fig. 6), the difference in the consolidation settlement of deep mixing pile corresponding to conditions with and without consideration of piezometric drawdown, respectively, can be derived as follows:

$$\left(\delta_{p,dd}\right)_{\Delta\sigma} = \left(\frac{C_{rp}}{1+e_{ot}}\right)\left(L_p - z_o\right)\mathrm{Log}\left[\frac{\sigma'_{vo}\left(\sigma'_{vo}+\Delta\sigma_{vdd,ave}+\Delta\sigma_p\right)}{\left(\sigma'_{vo}+\Delta\sigma_p\right)\left(\sigma'_{vo}+\Delta\sigma_{vdd,ave}\right)}\right] \quad (4)$$

where $\left(\delta_{p,dd}\right)_{\Delta\sigma}$ is the amount of overestimation of the consolidation settlement resulting from the underestimation of the initial overburdened effective stress by not considering the effect of piezometric drawdown; $\Delta\sigma_{vdd,ave}$ is the average drawdown pressure= $(1/2)\Delta\sigma_{vdd,bot}$ (see Fig. 6); $\Delta\sigma_{vdd,bot}$ is the magnitude of drawdown pressure at the bottom-end of deep mixing pile; σ'_{vo} is the initial overburdened effective vertical stress calculated not considering the piezometric drawdown at the midheight of the portion (L_p – z_o) which is the pile's portion subjected to piezometric drawdown (Fig. 6). In Eq. (4) the logarithmic function will always yield to negative result, i.e., the expression inside the logarithmic function is always less than unity.

Case 2: Increment of consolidation settlement due to increment of downdrag force

The increment in consolidation settlement resulting from the increment of downdrag force associated with piezometric drawdown can be obtained as follows:

$$\left(\delta_{p,dd}\right)_{neg} = \left(\frac{C_{rp}}{1+e_{ot}}\right)\left(L_{neg} - z_o\right)\mathrm{Log}\left[1+\frac{\frac{2\beta_{ave}}{d_p}\left(\Delta\sigma_{vdd,neu}\right)\left(L_{neg}-z_o\right)}{\sigma'_{vo,neu}+\frac{1}{2}\Delta\sigma_{vdd,neu}}\right] \quad (5)$$

where $\left(\delta_{p,dd}\right)_{neg}$ is the increment in consolidation settlement resulting from the increment of downdrag force associated with piezometric drawdown; $\Delta\sigma_{vdd,neu}$ is the magnitude of drawdown pressure at the level of neutral line of down-drag force (Fig. 6); $\sigma'_{vo,neu}$ is the initial overburdened vertical effective stress calculated not considering the effect of piezometric drawdown at the midheight of the portion (L_{neg}– z_o); L_{neg}– z_o is the portion of deep mixing pile subjected to downdrag and affected by piezometric drawdown (Fig. 6). Finally, the overall increment in consolidation settlement due to piezometric drawdown can be obtained by adding algebraically Eqs. (4) and (5) as follows:

$$\left(\delta_{p,dd}\right) = \left(\delta_{p,dd}\right)_{neg} + \left(\delta_{p,dd}\right)_{\Delta\sigma} \quad (6)$$

3.3 Overall consolidation settlement of deep mixing pile

The consolidation settlement of the deep mixing pile, $\delta_{p,t}$, is

$$\delta_{p,t} = \delta_{p,bot} + \delta_{p,\sigma n} + \delta_{p,dd} \quad (7)$$

where $\delta_{p,\sigma n}$ is the consolidation settlement due to the applied loading plus the induced downdrag force due to local differential settlement, calculated not considering the effect of piezometric drawdown as given in Eq. (1); $\delta_{p,dd}$ is the additional consolidation settlement due to the effect of piezometric drawdown as given in Eq. (6); $\delta_{p,bot}$ is the additional consolidation settlement due to the penetration of the deep mixing pile into the compressible layer below the pile tip. The consolidation settlement, $\delta_{p,bot}$, can be obtained using the standard method of settlement calculation.

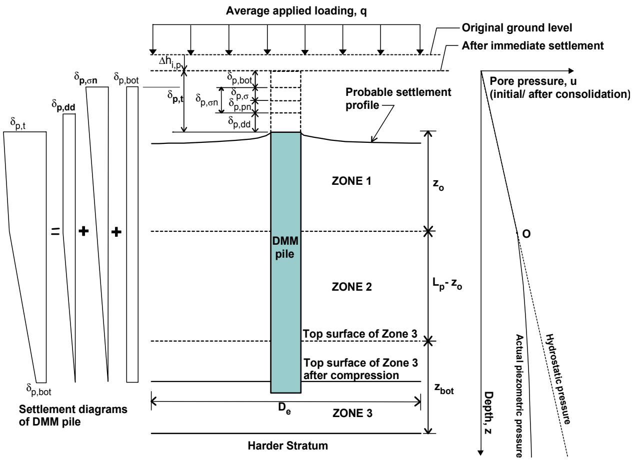
4 SUGGESTED SCHEME OF DMM PILE INSTALLATION FOR BRIDGE APPROACH FOUNDATION

Figure 7 shows the proposed scheme of deep mixing installation for foundation support of bridge approach embankment. The steps in determining the lengths of the DMM piles are as follows (Lorenzo, 2005):

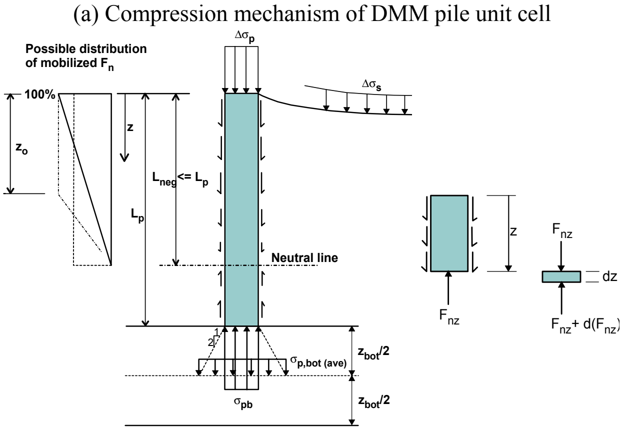
a) Obtain the essential data: cross-section of the highway; design speed; design load; geotechnical properties of the subsoils.
b) Locate the anticipated crown level after 20 years relative to the original one, and, then, choose the effective length of the deep mixing improved section, L_e, with due consideration of the requirements of minimum passing sight distances.
c) Using 0.50 or 0.6 m diameter DMM piles at 1.5 m spacing in square pattern, which are common in practice, determine the total settlement assuming the DMM piles are installed down to the bottom of the soft clay layer. This settlement is designated as 'S_1'. Determine the distance 'x' to locate P_1.
d) Determine the difference in elevation (S_2) between the original crown level and the anticipated realignment scheme at the point of reverse vertical curve (PVRC).
e) Determine the length of DMM piles that is enough to yield a total settlement of the embankment equal to S_2. Then, locate point P_2, the bottom of DMM piles at the PVRC.
f) Locate point P_3, which is located half-way of the vertical sag curve, i.e. $L_e/4$ from the point of vertical tangency (PVT).
g) Draw a line connecting P_2 and P_3. Draw horizontal line passing through P_1, and another one along the bottom of the weathered crust layer.

h) The smooth variation of the deep mixing pile tip is assumed to be parabolic. Draw the parabolic curves from P_1 to P_2 and, then, from P_2 to P_3. These curves define the location of the bottom ends of the DMM piles mentioned in ‘c’.

i) From point P_1, determine the reduced spacing of the DMM piles so that the estimated total settlement of the improved foundation equals to the difference in elevation between the original and the realigned crown level at the point in question. Make the necessary zoning of the spacing, as in Fig 7, for easy installation.



(a) Compression mechanism of DMM pile unit cell



(b) Downdrag skin friction due to local differential settlement

Figure 5. Analytical model for the compression mechanism of DMM pile.

5 CONCLUSIONS

The DMM pile installation in the soft clay foundation has reduced tremendously the compressibility and increased the lateral resistance of the soil. Not only the settlement of reinforced embankment was reduced by at least 70%, but also the rate of consolidation has accelerated amounting to 86% degree of consolidation, which was almost 90%, 1 year after embankment construction. The local differential settlement between DMM pile and the adjacent clay was observed in the full-scale improved foundation, and it amounted to 25 to 60 mm which were about 8% to 20% of the average settlement. This local differential settlement, however, was not obvious at the top surface of the embankment due to the combined effect of compaction as well as reinforcement stiffness and arching of the reinforced soil. The local differential settlement could induce downdrag skin friction (or negative skin friction) on the DMM pile.

The long-term settlement analysis for DMM improved ground, with and without piezometric drawdown, has been presented. In addition to the effect of piezometric drawdown, the effect of local differential settlement between pile and adjacent soil on the compression and bearing mechanisms of deep mixing pile was also illustrated and discussed. A method of proportioning the lengths and a typical layout of DMM piles for bridge approach embankment were presented. To avoid consequent undulation of the pavement at bridge approach, it is imperative that the DMM piles supporting the embankment must be installed at varying lengths, with closer spacing and full penetration through the soft clay layer at the zone near the abutment and, then, decreasing smoothly towards the determined length of improvement, as demonstrated in the proposed scheme. Significantly, the smooth variation of the lengths of deep mixing piles is as important as the smooth vertical alignment of the crown of the pavement.

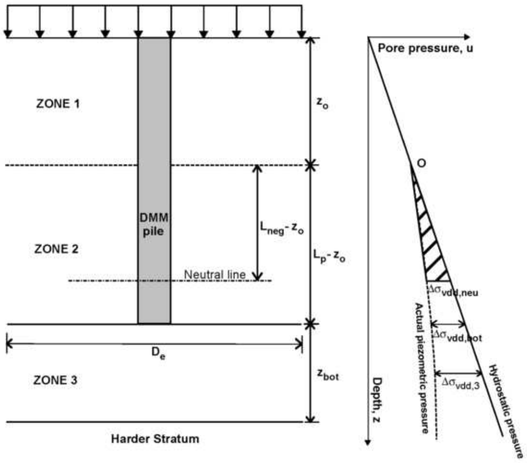


Figure 6. Blow-up diagram of DMM pile section subjected to piezometric drawdown.

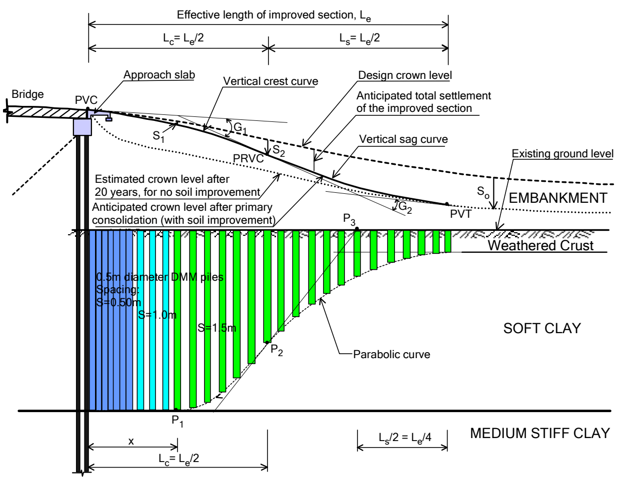


Figure 7. Suggested scheme of DMM pile installation for bridge approach embankment on soft clay ground.

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