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Numerical modelling of a pile-supported embankment using variable inertia piles

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Abstract. The increasing lack of good quality soils allowing the development of roadway, motorway, or railway networks, as well as large scale industrial facilities, necessitates the use of reinforcement techniques. Their aim is the improvement of the global performance of compressible soils, both in terms of settlement reduction and increase of the load bearing capacity. Among the various available techniques, the improvement of soils by incorporating vertical stiff piles appears to be a particularly appropriate solution, since it is easy to implement and does not require any substitution of significant soft soil volumes. The technique consists in driving a group of regularly spaced piles through a soft soil layer down to an underlying competent substratum. The surface load being thus transferred to this substratum by means of those reinforcing piles, which illustrates the case of a piled embankment. The differential settlements at the base of the embankment between the soft soil and the stiff piles lead to an "arching effect" in the embankment due to shearing mechanisms. This effect, which can be accentuated by the use of large pile caps, allows partial load transfer onto the pile, as well as surface settlement reduction, thus ensuring that the surface structure works properly. A technique for producing rigid piles has been developed to achieve in a single operation a rigid circular pile associated with a cone shaped head reversed on the place of a rigid circular pile. This technique has been used with success in a pile-supported road near Bourgoin-Jallieu (France). In this article, a numerical study based on this real case is proposed to highlight the functioning mode of this new technique in the case of industrial slabs.

Keywords: piled embankment; numerical modeling; soil/structure interaction

1. Introduction

The lack of good quality soil areas to develop roadways, motorways, and railway networks, as well as industrial areas, necessitates the use of improvement techniques for soft soils. One of this technique to reduce the surface settlements involves the use of vertical stiff piles. This technique is fast to implement and does not require the replacement of soft soils; it consists of a grid of piles driven through the soft layer and embedded in an appropriate underlying substratum, with a granular earth platform or embankment placed above the piles.

The differential settlements at the embankment base between the soft soil and the stiff piles lead to an arching effect in the embankment due to shearing mechanisms. This arching permits a partial load transfer onto the pile as well as surface settlement reduction and homogenization. It thus permits to ensure the durability and the functionality of the surface structure. Friction along the pile also contributes to the system behavior in the improved soft ground (Okyay and Dias 2010, Chore, Ingle *et al*. 2014). The soft soil settles more than the piles in the upper portion of the stratum, leading to negative skin friction and increasing the load transfer onto the piles. In the lower portion, the piles punch into the substratum and settle more than the soft soil, leading to positive skin friction and the development of toe resistance (Jenck *et al*. 2005, Doran *et al*. 2014).

This technique is primarily applied to road and railway embankments (Almeida, Magnani *et al*. 2011, Quigley, O'Malley *et al*. 2003, Wood 2003, Zanziger and Gartung 2002, Okyay, Dias *et al*. 2014, Shankar, Loganathan *et al*. 2015). Road widening is also a major application area (Habib, Brugman *et al*. 2002) because it overcomes the problem of differential settlement between old and new road sections.

The traditional process involves the completion of a regular grid of circular rigid piles (with constant area). In order to have a larger pile contact area to allow a better distribution of the efforts to the piles, an increase of the pile head section is possible, while maintaining an identical pile shaft area.

This construction process already exists in the form of squared concrete slabs placed on the head of the pile. The major drawback of this device is the fact that it necessitates two separate interventions (completion of the pile and installation of the the precast slab) and is difficult to set up. The concept of rigid piles with variable inertia permits therefore to produce a circular pile associated with a conical head. It can be realized in one time and ensure the continuity of the inclusion.

Determination of the load distribution at the platform base is a major concern for pile designs. Several design methods exist, based on various concepts for assessing the

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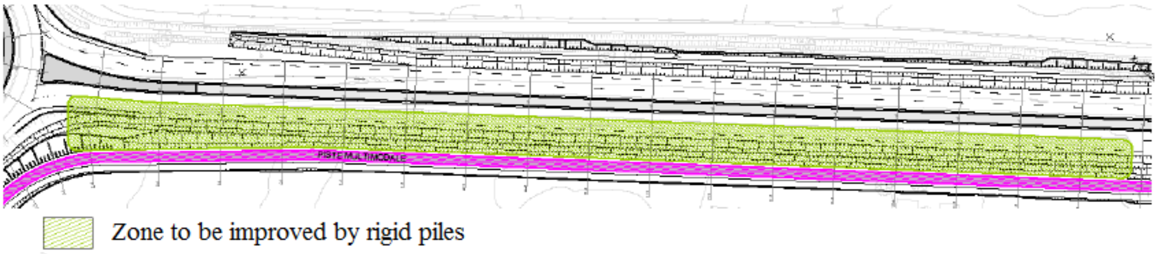


Fig. 1 Improvement work (Exbrayat, Nancey *et al*. 2011)

arching effect.

The Hewlett and Randolph (1988), Kempfert, Göbel *et al*. (2004) methods are based on analytical vault shape models. The Combarieu (1988) method is based on negative friction along a concentric surface in the soft soil, as well as in the embankment fill. The Russell and Pierpoint (1997) approach is based on the Terzaghi (1943) theory and considers the equilibrium of the soil zones situated above the soft soil. The Svano, Ilstad *et al*. (2000) approach considers that a wedge of embankment fill is supported by each pile. It is important to notice that only the Combarieu (1988), Low, Tang *et al*. (1994), Kempfert, Göbel *et al*. (2004) methods consider the presence of the soft subsoil. Nevertheless, these current design methods provide different results for the same situation (Jenck, Dias *et al*. 2005. Nunez, Briancon *et al*. 2013), and none of these methods can truly represent the actual behavior of the system. Moreover, Love and Milligan (2003) note many further considerations which must be addressed by designers; for instance, the relationship between the settlements that occur at the embankment base and the settlements that will occur at the surface, the effect of cohesion and dilation in the embankment fill, and the effect of a crust on the soft soil at ground level.

The problem studied here is typically three-dimensional (3D), primarily due to the vaulted shape in the embankment (Briançon and Dias 2015, Dias and Simon 2015, Okyay and Dias 2010, Rajib, Sekhar *et al*. 2015). In the case of a square grid of piles, each vault rests on four pile caps. Kempton, Russell *et al*. (1998) compared a two-dimensional (2D) plane strain modeling to a 3D numerical modeling and showed that the 2D modeling cannot properly simulate the actual system behavior (Girout, Blanc *et al*. 2014, Hassen, Dias *et al*. 2009, Mehndiratta, Sawant *et al*. 2014). Therefore, a full 3D calculation appears necessary to represent the actual system behavior. However, 3D simulations of piled embankments that explicitly represent the embankment and the improved soft ground are rare and recent (Jenck, Dias *et al*. 2007, Jenck, Dias, *et al*. 2009a, 2009b, Stewart and Filz 2005, Mohammed, Mustafa *et al*. 2015) because the models are large and time consuming.

Moreover, 2D axisymmetric simulations represent the vaults as “umbrellas,” which does not completely represent reality (Naughton 2007). This type of modelling gives results with a good accuracy compared to a 3D modelling. The error between axisymmetric and 3D models is less than 9% (Nunez, Dias *et al*. 2007).

This paper presents an industrial structure project on which a variable inertia pile improvement was used. Based on the results of the geotechnical investigation, a finite element analysis has been developed. The numerical study based on this real case is presented to highlight the functioning mode of this new technique in the case of industrial slabs.

2. Project description

2.1 General information

As part of the creation of a hospital complex in the town of Bourgoin Jallieu (France), the French government has decided to create a 2×2 road by extending the existing road and creating a roundabout by setting up embankments on compressible grounds.

The improvement work by rigid piles (Fig. 1) has been done over a length of about 400m. The initial solution consisted of the creation of rigid piles associated with precast concrete slabs. Another innovative solution has been proposed: the creation of circular rigid piles of 0.35 m diameter with an extended head diameter (rigid piles with Variable Inertia) in a regular grid to deal with highly compressible soils.

The rigid piles with variable inertia have been associated with horizontal geotextile reinforcement before the embankments realization and the creation of the pavement. The choice of the rigid piles with variable inertia has been done for several reasons as its easy completion (no necessary to handle precast concrete slabs), the time reduction, the increase of efficiency and the significant savings in concrete and steel.

2.2 Geotechnical context

The work site (Fig. 2, before improvement) is an ancient swamp more or less dry with a water table at shallow depth. The various geotechnical investigations have highlighted the following lithological succession:

- A cover of sandy clay brown to blackish,
- Peat brown to black with its base of small decomposed plants,
- Predominantly alluvial clay, plastic, gray to beige, soft to very soft (named clayey sand),
- A compacted sandy gravel layer.

The bedrock layer is located at about 8.3 meters above the ground surface (which is located on the top of the sandy clay clayer).

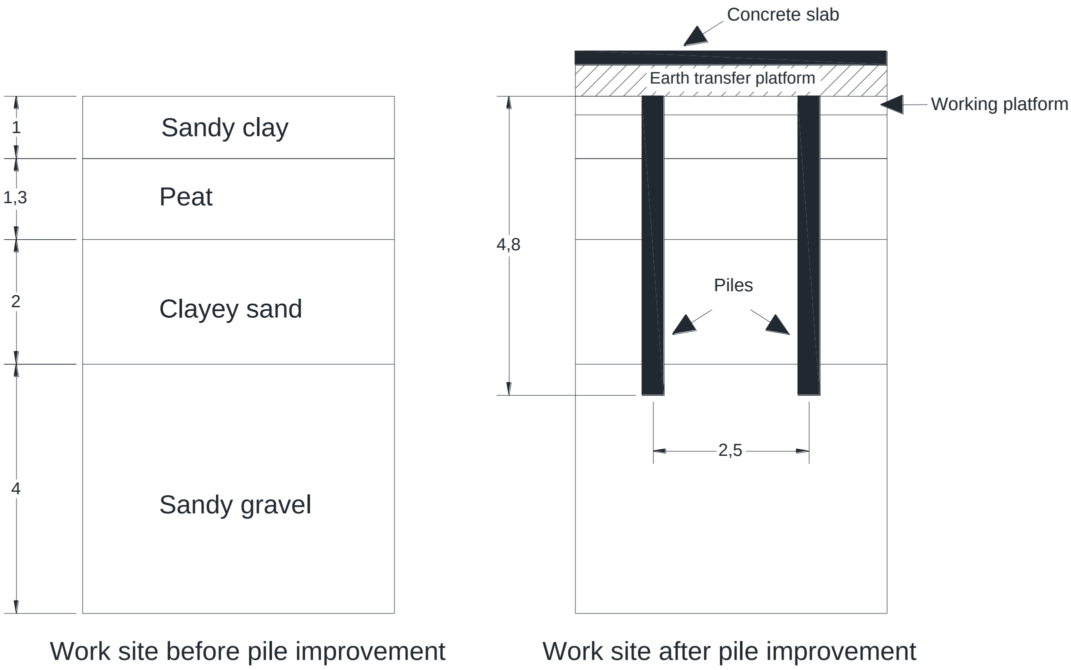


Fig. 2 Work site before and after improvement

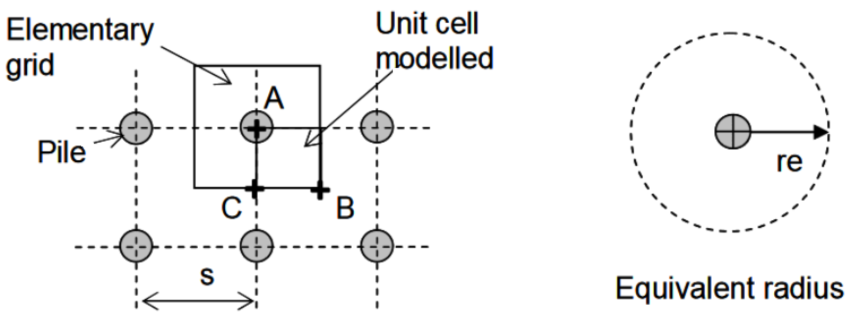


Fig. 3 Passage from the 3D to a 2D axisymmetric model

3. Numerical modelling

The numerical study presented in this paper aims to better understand the behaviour of piled earth platforms using rigid piles with variable inertia. This study uses the real geometry and properties for the constitutive materials of the Bourgoin-Jallieu site (France). The numerical study presented hereafter is done using the finite element code Plaxis (Plaxis 2016).

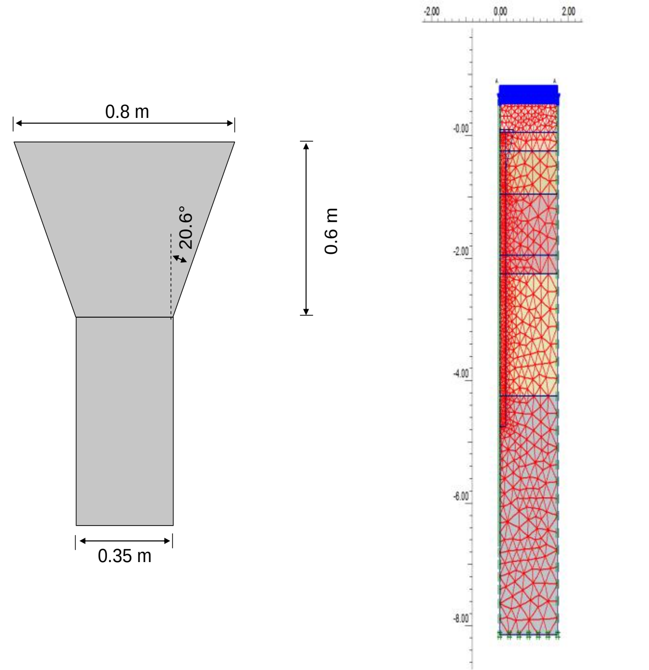
A unit cell of a regular square grid pattern of 2.5 m is considered (Fig. 2, after improvement). Fig. 3 shows the top view of the pile grid part and indicates the unit cell simulated in the numerical model. The 3D geometry is simplified to a two dimensional axisymmetric one (Nunez, Dias *et al*. 2007) with an equivalent radius of 1.41 m.

An axisymmetric finite element model was defined using 15-noded triangular elements.

Due to 2D axisymmetric conditions, the nodes on the vertical boundaries were fixed in their horizontal direction, while the nodes at the base of the model were fixed in both directions to simulate the presence of a bedrock. The adopted depth for the bedrock was the one given by the onsite investigations. The mesh was refined around the pile and in the mattress where shearing mechanisms will occur during the loading.

The introduced geometry (Fig. 4(b)) has 4.3 m high of homogeneous compressible horizontal soil layers (Sandy clay, peat and clayey sand) supported by 0.35 m of diameter piles. The piles are 4.8 m of depth with a spacing of 2.5 m. On the sandy clay, a working platform of 0.3m high has been created. The earth platform of 0.5 m height was placed over the piles. Fig. 4(a) shows the detail of the variable inertia pile head taken as the reference case in the following study. The reference case of this study is developed to take into account the presence of a structure at the surface. A concrete slab of 0.22 m thickness is placed over the earth platform. A surcharge of 25 kPa is then setup on this structure tatic equilibrium under self-weight is reached at each loading stage. The following six loading stages were set up for each calculation:

- Initial stage: Set up of the working site soils (Fig. 2, before improvement),
- Excavation of 0.3 m of the top of the sandy clay layer and set up of the working platform,



(a) Detail of the rigid pile head (reference case)   (b) Numerical model

Fig. 4 Developed model

Table 1 Geomechanical parameters for the soils simulated using the Soft Soil model

Soil layer	C_c	C_s	e_0	ϕ'(°)	γ (kN/m^3)
Sandy clay	0.45	0.04	1.17	29.4	18
Peat	1.31	0.13	2.46	19.3	15
Clayey sand	0.45	0.04	1.17	23.2	18

Where C_c is the compression index, C_s is the swelling index, e_0 is the initial void ratio, ϕ' is the friction angle and γ is the volumic weigth

- The vertical piles are set up. The effect of pile installation is not taken into account,
- The volume elements, corresponding to the earth transfer platform layer are then activated,
- Set up of the concrete slab,
- The additional surcharge of 25 kPa on the top of the concrete slab is then applied.

Geotechnical tests (oedometer, triaxial, a loading test and penetrometers) have permitted to obtain the geomechanical characteristics of the soil layers. 10 kPa of over-consolidation was initially applied to the sandy clay layer. The constitutive model adopted for the compressible layers is the Soft Soil Model implemented in Plaxis (Plaxis 2016). Table 1 presents the geomechanical parameters for these layers.

For the other soil layers (earth transfer platform, working platform and sandy gravel), a linear elastic perfectly plastic with a Mohr Coulomb criterion has been adopted (Table 2). For the structural elements, linear elasticity has been used. All the numerical calculations have been done in drained conditions.

Table 2 Geomechanical parameters for the other soil layers and for the structural elements

Soil layer	E (MPa)	v	ϕ' (°)	C' (kPa)	ψ (°)	γ (kN/m^3)
Earth transfer platform	50	0.3	35	0	5	20
Working platform	30	0.3	30	0	0	19
Sandy gravel	90	0.3	41	10	5	19
Concrete slab	11000	0.2				25
Vertical pile	8000	0.2				25

Where E is the Young's modulus, v is the Poisson's ratio, ϕ' is the friction angle, C' is the drained cohesion, ψ is the dilatancy angle and γ is the volumic weigth

Frictional interfaces were placed between the pile and compressible soil layers. An ultimate skin friction parameter q_s=30kPa was used. The installation effect of the bored piles was not considered.

The numerical calculations were analysed in terms of stress efficacy. Authors propose the term of efficacy in order to determine the effectiveness of reinforcement. (Terzaghi 1943, Hewlett and Randolph 1988, British Standard BS8006 1995, Guido, Kneuppel *et al.* 1987, Russell and Pierpoint 1997, Rogbeck, Gustavson *et al.* 1998). Stress efficacy is the ratio between the load transmitted to the head of the pile and the total load on the unit grid.

Another parameter has been defined the settlement efficacy which represents the settlement reduction given by the pile reinforcement compared to a free field. The definition of this ratio is

$$E_{Settl} = 1 - \frac{S_{\text{reinf}}}{S_{\text{unreinf}}} \tag{1}$$

Where S_{reinf} is the settlement of the soil mass with pile reinforcement and S_{unreinf} without pile reinforcement.

4. Results

4.1 Reference case

For the reference case, Fig. 5 shows the vertical displacement field in the soil mass. The maximum vertical displacement is located at the interface between the working platform and the mattress between the two piles. Fig. 6 permits to clearly identify the neutral point where foundation soil and piles settlements are equal and where the pile is vertically loaded at its maximum. At this point the maximum vertical stress on the rigid pile is equal to 2490 kN/m^2.

In the reference case the bending moment reaches the value of 14.08 kN.m/m.

An interesting point is the distribution of the skin friction along the pile (Fig. 7). In the case of variable inertia piles reinforcement, the friction is only saturated at the pile

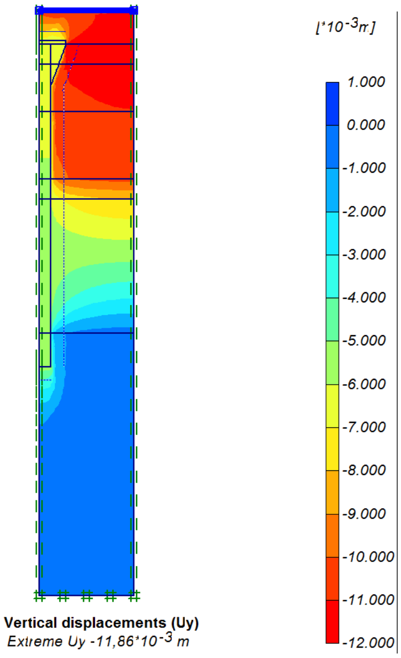


Fig. 5 Vertical displacements

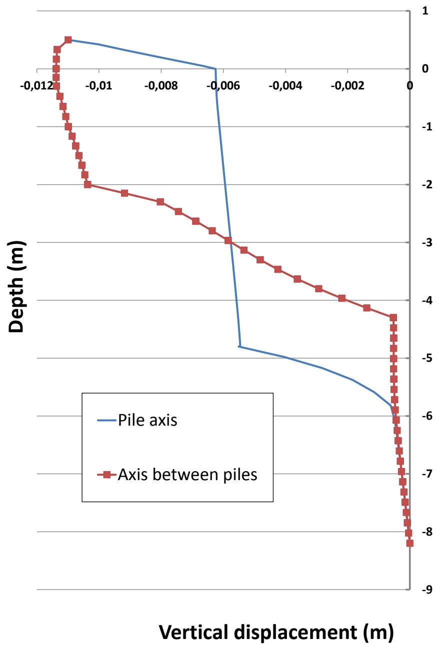


Fig. 6 Vertical displacements on the pile and between two piles

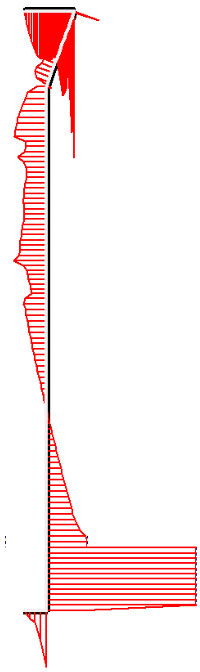


Fig. 7 Friction along the pile (maximum value 110 kPa)

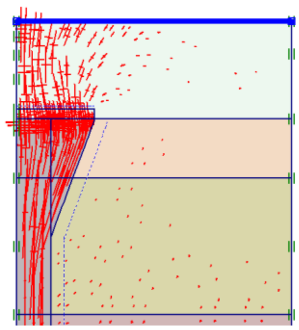


Fig. 8 Principal stresses distribution (Extreme total principal stress 2.21MPa)

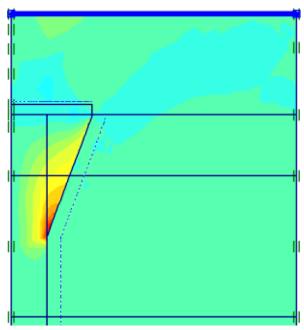


Fig. 9 Shear stress distribution

toe (i.e., ultimate skin friction reached). This is due to the inclination of the pile head which does not permit to increase the friction in the first 0.6 m. In this zone, the negative friction cannot be developed and is then transferred to the layers above. In this case, an attentive care on the friction conditions at the bottom of the pile must be taken. In terms of loading in the reinforced area, due to the small height between the pile head and the slab complete arching cannot occur and a stress concentration occurs on the zone at the top of the pile (Fig. 8).

Due to the inclination of the pile head, a tension concentration of 0.5 MPa (Fig. 9) appears at its corner. The concrete of the vertical pile can therefore sustain a maximum tensile stress of 1.2 MPa.

4.2 Influence of the mattress thickness

The study of the mattress thickness influence (Fig. 10)

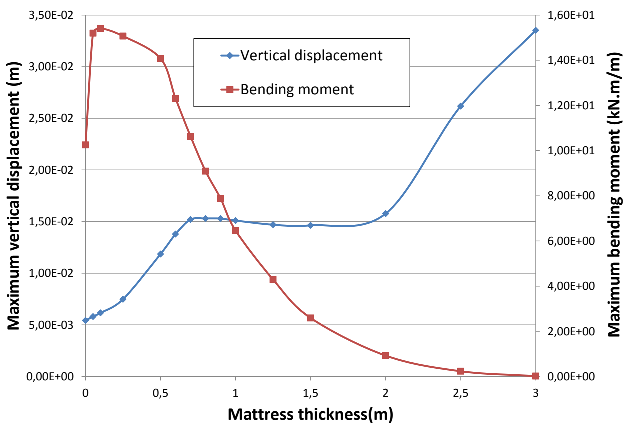


Fig. 10 Maximum vertical displacement and maximum bending moment vs mattress thickness

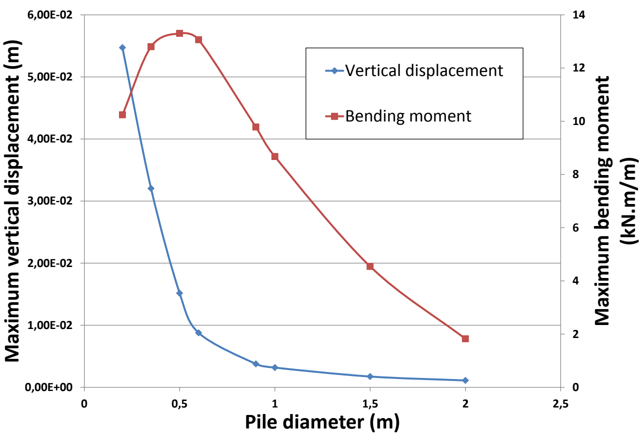


Fig. 11 Maximum vertical displacement on the soil and bending moment on the slab versus the upper head diameter

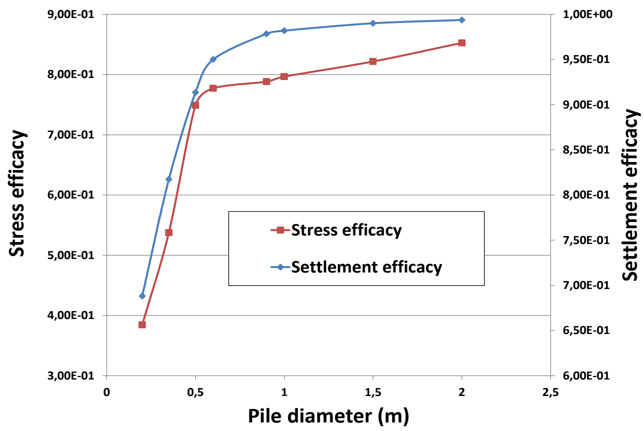


Fig. 12 Stress and settlement efficacy

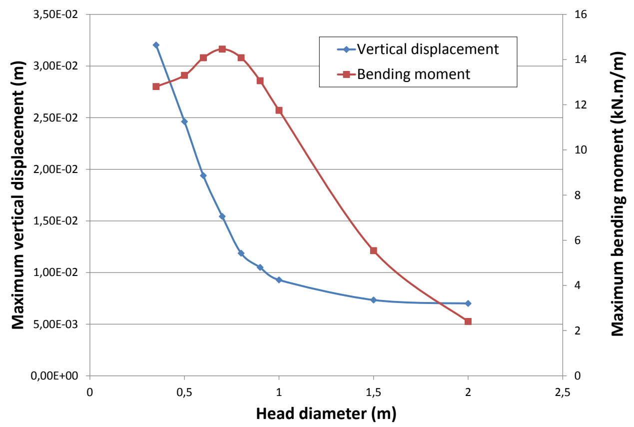


Fig. 13 Maximum vertical displacement on the soil and bending moment on the slab versus the upper head diameter

highlights the required thickness necessary to develop complete arching. It can be seen that with a mattress thickness higher than 0.70 m (reference case), a decrease of the bending moment is observed. This effort reaches a negligible value for a mattress thickness equivalent to the distance between piles. It is therefore not necessary to increase the thickness of the mattress to values higher than one meter to allow the development of the arching effect.

4.3 Influence of the rigid pile diameter

To better show the influence of a variable inertia pile head, a preliminar study considering a circular conventional pile has been done. The influence of the pile diameter has been investigated by a parametric study based on the reference case. The pile diameter has been modified on a range between 0.35 m to 2 m.

Fig. 11 shows the evolution of the maximum displacement with the increase of the pile diameter. The decrease of this parameter is important till a diameter of 0.50 m, after this value the vertical displacement reaches a threshold. In terms of bending moment in the slab, this value of the pile diameter is an interesting zone where the evolution of bending moment changes. Before this value, an increase is observed until a maximum of 13 kNm. After a decrease can be observed.

In the reference case, a pile diameter of 0.7m corresponds to the case where the slab is the more loaded and then its contribution to the displacement limitation is the highest. For higher values of the pile diameter, the curvature of the slab is lower due to the pile diameter and then the bending moment decrease. These results depend on the height of the mattress (which was a constant for the parametric study).

Considering the efficacies (Fig. 12), the stress and the settlement efficacies have the same tendency. They increase with the increase of the pile diameter.

4.4 Comparison with a variable head diameter (variable inertia piles)

To compare the behavior of the circular piles with the variable inertia ones, a parametric study on the pile head diameter has been done. The diameter of the lower part of the pile was fixed to 0.35 m, then the head diameter has been modified in the range from 0.35 m to 2 m.

The behavior of rigid piles with variable inertia is quite close to the behavior of circular piles. The first curve shows a decrease of the vertical settlements until a plateau and at the same time for the bending moment an increase and then

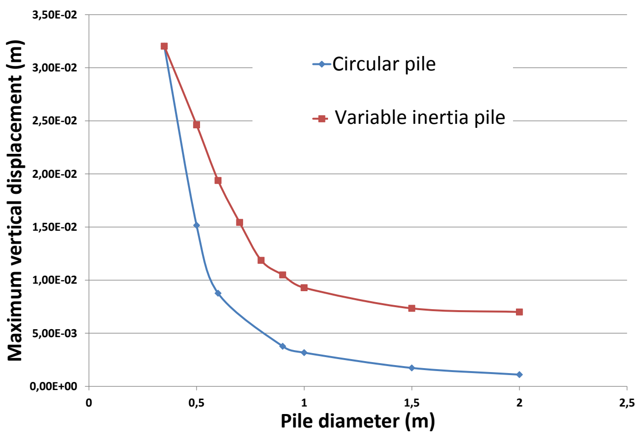


Fig. 14 Comparison in terms of maximum vertical displacement between circular and variable inertia piles

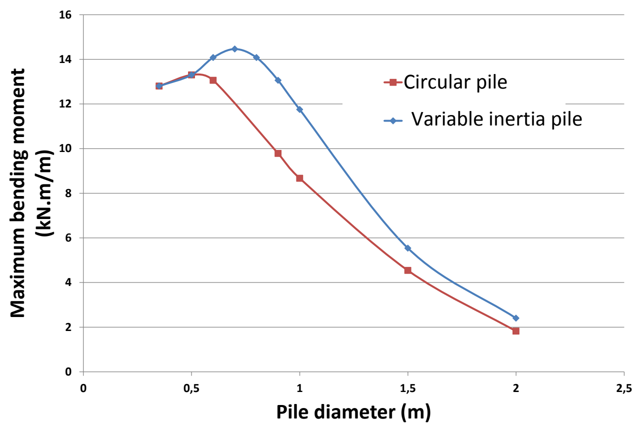


Fig. 15 Comparison in terms of bending moment between circular and variable inertia piles

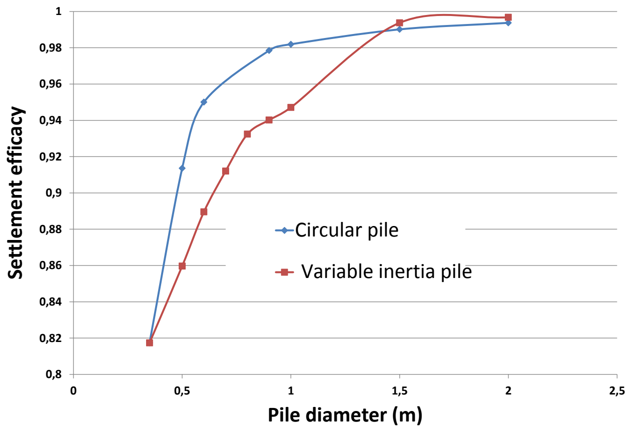


Fig. 16 Comparison in terms of settlement efficacy between circular and variable inertia piles

Table 3 Volume of the piles

Pile head diameter (m)	0.35	0.50	0.60	0.70	0.80	0.90	1.00	1.50
Volume of the circular pile (m^3)	0.46	0.94	1.36	1.85	2.41	3.05	3.77	8.48
Volume of the pile with variable inertia (m^3)	0.46	0.49	0.51	0.54	0.57	0.60	0.64	0.86

a decrease of the bending moment with a passage by a peak for a value of the pile diameter head of 0.7 m (Fig. 13).

The comparisons between these two types of piles will be always done considering the same pile head diameter.

Fig. 14 shows the comparison between these two types of piles in terms of vertical displacements. One can see that for the same pile head diameter, the circular piles are more efficient and permit to better reduce the settlements at the interface between the working platform and the mattress.

The same tendency is observed for the bending moments (Fig. 15). The circular piles are more efficient (Fig. 16). It is due to the relative displacements of the soils at the pile head corner which are higher in the case of the variable inertia pile. However, the volume of incorporated material is significantly lower (Table 3) in the case of a rigid pile with variable inertia compared to the case of a circular pile of the same head diameter (76% less for a head of 0.8 m diameter).

Comparing piles with variable inertia (head diameter of 0.80m and shaft diameter of 0.35 m) and circular piles of 0.35m diameter, the reduction of the vertical settlements is much larger (decrease of 63.2%) in the first case. However, the induced bending moment in the pavement is more important in the case of variable inertia piles (increase of 7.4%).

5. Conclusions

The functioning mode of the variable inertia piles is different from the one of classical circular piles. The negative friction cannot be totally developed at the pile head and then the efforts are redistributed along the pile shaft. A higher attention of the friction conditions at the pile toe must then be paid.

The comparison of the variable inertia piles with the circular ones has shown that they have the same behavior if the bending moments in the slab or the stress and settlement reduction are considered.

With the same head diameter, circular piles permit a higher reduction of the vertical settlements and of the induced bending moment in the pavement. However, the necessary volume of the material to be included is much larger in this case.

By comparing piles of variable inertia (reference case) and the circular piles with the same shaft diameter, the decrease of the vertical settlements is more important in the case of variable inertia piles. However, the moment induced in the pavement by including variable inertia piles remains larger.

The enlargement of the head diameter to 1.00 m permits for the variable inertia piles to be more effective than circular piles of the same shaft diameter in terms of vertical settlements reduction and also in terms of bending moments in the pavement.

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