Subsidence Control of Construction on Soft Soils with *"Akar Foundation"*

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Abstract

Good quality soils are always preferred in development projects, where the bearing capacity of the grounds is sufficiently high and the resulting subsidence is non-excessive. However these sites may not be as readily available with increased population and land use, making it inevitable to construct on less favourable soils, like soft organic materials. To ensure long term stability of structures erected on such soft soils, elaborate and extensive foundation systems are generally required. Alternatively, pre-treatment with ground improvement techniques is necessary. Both these methods tend to incur high costs and labour as well as require prolonged construction period, while making a rather negative impact on the environment in terms of raw material sourcing, heavy machinery mobilization and exposure to the risk of groundwater contamination. This paper describes an exploratory study on a simple shallow foundation system for construction on soft soils, which can be a potentially cheaper and more sustainable approach. The foundation system, termed the *"Akar Foundation"*, literally translates as "Root Foundation", is essentially a lightweight platform supported by a group of hollow stumps (i.e. PVC pipes). The 'root' base served dual functions: 1. to collectively assert a stronger grip of the soft soils, hence giving higher bearing capacity; 2. to spread the imposed structural load evenly into the subsoil, thus avoiding excessive and non-uniform settlements. The effects of the end condition of the pipes (i.e. open or close) as well as the spacing between the pipes on the foundation settlement mechanism were examined, with static load tests conducted using a lab-scale simulation chamber. The findings showed that the effectiveness of the *"Akar Foundation"* depends on the compatibility of the pipe spacing and individual pipe lengths, highlighting the inter-relationship between the mobilisation of end resistance, skin friction and formation of soil plug in the open-end system. In a promising light, the reduced subsidence suggest the potential of the *"Akar Foundation"* as an economical yet effective foundation system in economically challenged soft soil areas.

Keywords: Shallow foundation, Soft soils, Subsidence

1. Background: Problems and Current Practice

Construction on soft soils, such as organic and peat soils, has always been considered a challenging task by the civil engineering community. Low strength and high compressibility are typical characteristics of such soils, making them inadequate to support the additional load of infrastructure built on them. Some additional considerations are required to provide a sufficiently strong foundation to support the development above ground. The foundation has to not only bear the dead and live loads without collapse, but also to undergo limited and uniform settlement with time.

Organic soils are commonly found as extremely soft, unconsolidated superficial deposits that are an integral part of the wetland system (E.P.M. Jarret, 1995). They are recognized as problematic materials for their notoriously low shear strength, high compressibility and permeability as well as considerable secondary compression or creep characteristics (P. Kallioglou *et.al*, 2009). A main constituent of these soils is the organic matter, which encompasses any organic compound contained in the soil, with the exception of living biomass. The organic matter consists of humus, dead vegetable and animal biomass, water-soluble organic compounds, and other non-living organic substances or organo-mineral components (C. Siewert, 2002).

In Malaysia, peat and organic soils are considerably extensive, making development on such areas a challenging endeavour for civil engineers. A.A. Mutallib *et al.* (1991) reported that these deposits represent some 8 % of the total land area of the country, which is equivalent to approximately 2.6 million hectares of land area. Organic soils in particular, have an inhomogeneous and anisotropic structure that differs greatly from inorganic soils, resulting in their peculiar engineering properties (P. Kallioglou *et al*., 2009), which are usually not condusive for load-bearing. These soils are commonly water-logged and contain high percentage of organic matters at different decomposed stages. The Malaysian peat, for instance, is usually found at sites with high water levels all year round, thus providing very limited resistance against loading and settlement in short or long term (C-M Chan and Z. Abu Talib, 2008), where even a moderate load can lead to a large change in volume in these soils (Huat, 2002).

The common foundations adopted for these areas are installation of deep and closely spaced piles. While the piles serve the purpose well by transferring the load to a firm stratum deep down in the subsoil, the scale of machinery, materials, labour, costs and time involved are inevitably high. Sometimes such approach may prove to be uneconomical and even unwise with over-designs to counter the poor soil quality. High safety factors may be used to ensure the performance of the foundation, hence leading to the installation of deep, closely spaced piles to mobilize optimal skin friction and end bearing capacities.

Floating foundations have also been used successfully in the construction on soft soils. A floating foundation is simply defined as a foundation of which the weight of the building is approximately equal to the full weight, including water, of the soil removed from the site of the building (V.N.S. Murthy, 2002). The foundation could be a raft or a mat, typically cast as a continuous reinforced concrete pad under the entire building (Carson Dunlop and Associates, 2003). Alternatively, a backfill of suitable material, as in the mass replacement method, is an option for providing a firm foundation for development on soft soils. The depth, however, should not exceed 6 m to ensure its effectiveness (J.P. Magnan, 2002).

Over the years, floating foundations have undergone significant innovations with the introduction of lightweight materials, effectively reducing the tendency and risk of subsidence under the foundation's own weight. This has made lightweight foundations a popular choice for construction on soft soils such as peat and organic soils (T.E. Frydenlund and R. Aaboe, 1997). A successful application of lightweight foundation systems was reported by the Norwegian Geotechnical Institute (NGI), where expanded polystyrene (EPS) was used as the foundation material in a housing scheme (R. Lauritzsen and J.T.H. Lee, 2002). Due to its light weight, very little pressure was exerted on the existing ground, hence minimising stability and settlement problems. The foundation installation involved excavation of the soft soil and placement of the polystyrene blocks, which then floated over the underlying ground. Nevertheless it was cautioned by B.B.K. Huat and R. Muniandy (2002) that the construction procedure requires a stable groundwater table as any changes can alter the state of buoyancy, leading to detrimental movements in the system as a whole. R. Lauritzsen and J.T.H. Lee (2002) also noted the importance of taking into account uplift pressure in a flooding situation to avoid heaving of the lightweight foundation system.

For the construction of smaller structures, such as individual dwellings, R.P Hadmodjo (1991) from Indonesia proposed the use of the locally termed *"Cakar Ayam"* or "Chicken Feet" foundation system, which was first developed by Seditjamo in the 1960's. The system consisted of a reinforced concrete slab resting on a number of reinforced concrete pipes. The soil and the pipes were modelled as isoperimetric solid elements, while the slab was modelled as an isoperimetric thick-plate element. Reportedly, passive soil pressure created a still condition of slab-pipe system, enabling the thin concrete slab to float on the supporting soils with the pipes kept in vertical positions due to the passive pressure. One prominent feature of the *"Cakar Ayam"* foundation system was the inside of the concrete pipes that were initially filled with in-situ soil, presumably to seal the open ends of the pipes for increased end resistance. This inadvertently increased the self-weight of the foundation, and could have offset some effectiveness of the system itself when loaded.

2. *"Akar Foundation"*: Origin and Design Concept

The origin and design concept of the *"Akar Foundation"* drew from both the floating foundation principles as well as the *"Cakar Ayam"* foundation system mentioned above. The word "akar" comes from the local Malay vocabulary, literally meaning "roots". Trees of various proportions and sizes stand tall with stability provided by the extensive root network system. With their natural survival instinct of reaching water sources underground, these extensive live tentacles of a tree penetrate and grip the soil as they grow and expand, eventually developing a formidable foundation to support and uphold the main trunk and upper ground parts of the tree.

It was thought to be an apt name as the foundation system is essentially a firm base supported by a network of root-like stumps beneath it, which grips the soft soil and spreads the load over the subsoil, thus giving the impression of "floatation" to the entire foundation system. The root network concept resonates with that of the subsurface activity of live roots of trees described earlier, which constitutes the first definition of the 'floating' concept.

Theoretically speaking, a floating foundation has the weight of the structure balanced by the removal of soil and construction of an underground basement, where the total load imposed by the structure is less or the same as the weight of the removed soil. The supporting soil layer will then be 'fooled' into believing that the sustained load has not changed or altered (which is true but the form of load is changed), and therefore will not settle or subside. The *"Akar Foundation"* works on similar principles, spreading and distributing additional structural load on the soil over a wider area with the root network. This gives the second definition of the 'floating' concept adopted in the development of this foundation system.

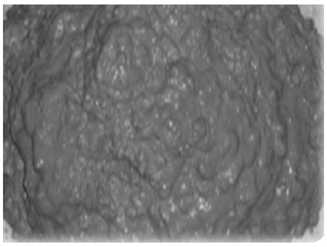
Different from the *"Cakar Ayam"* foundation system, the self-weight of the *"Akar Foundation"* was reduced by incorporating lightweight components: a light platform and polyvinyl chloride (PVC) pipes that function as stumps carrying and transferring the load. The platform can be made of foam for instance, or any locally available but suitable products, if cost minimization is a top priority. The PVC pipes can be cut-offs retrieved at a low price from manufacturing plants, or on a larger scale, produced from recycled plastic as an additional 'green' value to the system.

3. Experimental Work

The miniature *"Akar Foundation"* foundation model was made of a piece of 100 mm x 100 mm x 10 mm thick plywood and PVC pipes of 22 mm external diameter and 15 mm internal diameter. 3 sets of PVC pipes, measuring 25, 50 and 75 mm in length, were spaced equally at 34 mm or 51 mm centre-to-centre and glued to the bottom of the plywood. For illustration purposes, the arrangement of pipes for the 34 mm spacing system is shown in Figure 1. A pair of models were prepared for each set of pipes (i.e. equal pipe lengths), one with open-end pipes and the other with close-end ones. Note that the close-end pipes were left empty inside as opposed to the *"Cakar Ayam"* system, where the pipes were filled with in situ soil. Figure 2 shows the plan and side views of the inversed close-end foundation model with 34 mm spacing.

The load test was simulated in a glass chamber of 300 mm x 300 mm x 300 mm. An organic clay sample collected from Melaka was remoulded and used as the soil bed in the chamber at its natural water content. Properties of the soil were determined based on BS 1377 (1990), and the results are given in Table 1.

Table 1. Properties of the soil.

Properties	Values	Soil sample
Natural water content, w_N (%)	120	
Liquid limit, w_L (%)	145	
Specific gravity, G_s	1.92	
pH	3.45	
Fibre content (%)	26.7	
Loss on ignition, LOI (%)	84.9	

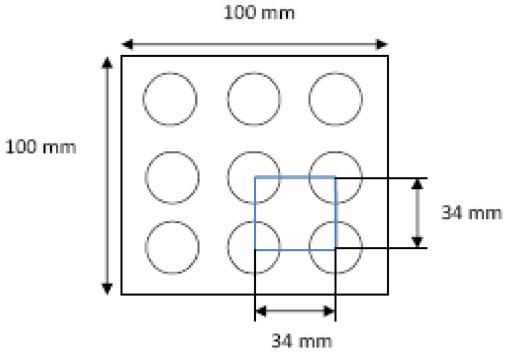


Figure 1. Arrangement of the PVC pipes in the *"Akar Foundation"* model (34 mm spacing)

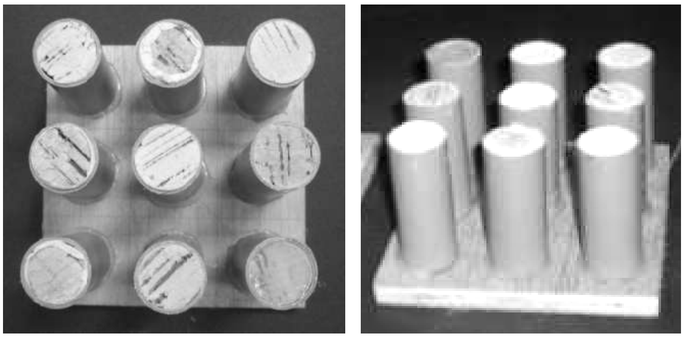


Figure 2. The miniature *"Akar Foundation"* model (34 mm spacing; close-end)

The soil sample was first remoulded in a separate container, then covered and left overnight prior to being used to form the soil bed in the test chamber (Figure 3). The purpose of this procedure was to allow uniform redistribution of moisture within the soil mass after the disturbance it underwent during sampling and transportation.

On the following day, the soil sample was transferred to the glass chamber to form the soil bed by lightly compacting 4 layers of wet soil weighing 6 kg each. The compaction was necessary to avoid entrapment of large quantities of air within the soil voids, which can cause errors in the settlement measurements during load tests. The compacted height of each layer was carefully monitored to ensure uniformity in the soil bed overall density (Figure 4). The final thickness of the soil bed was fixed at 200 mm, measured from the base of the chamber.

For the load test, dead weights were placed on top of the miniature foundation model to exert vertical stresses in the sequence of 0.25, 0.50, 0.75, 1.00 and 1.25 kPa (Figure 5). The vertical displacement under each load was recorded at prescribed time intervals of 5, 10, 15, 30, 60, 120, 240, 480 seconds, and finally terminated after a time lapse of 16 minutes (i.e. 960 seconds). A control test was also included in the test programme (i.e. sample Control), with only the plywood platform placed on the soil bed and loaded accordingly.

Figure 3. Remoulded soil left to cure overnight

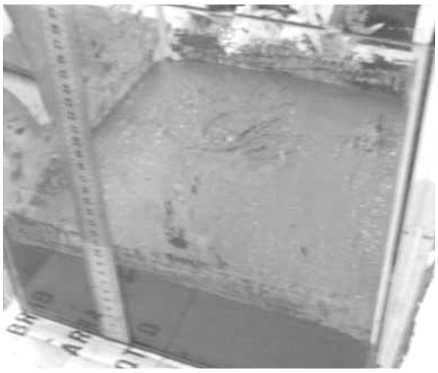


Figure 4. Preparation of the soil bed

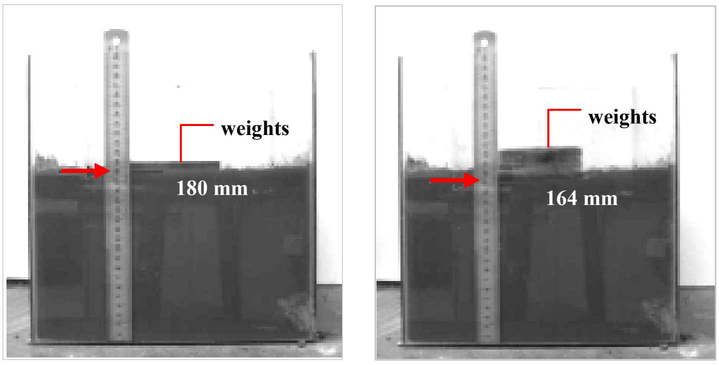


Figure 5. Load test of the foundation system: the arrow marker indicates the soil bed level (settlement) under different loads

4. Results: Analysis and Discussions

4.1 Rate of Settlement

Judging from the gradients of the settlement-time plots of Figures 6 and 7, settlement rates did not vary significantly between the open-end and close-end systems. This could be attributed to the intended ‘floating’ mechanism of both systems, where the applied stress was evenly spread over the contact surface between foundation and soil. By taking a closer look at the manner in which the plots unfolded, most settlements took place within the first 8 minutes. As these settlements were maintained for a short time lapse of just over quarter of an hour, prevalence of the undrained loading conditions were only to be expected. The pipes were likely to be pressed into positions of stability in bearing the load and transferring it to the surrounding grounds.

For the pipes spaced at 34 mm centre-to-centre apart, the close-end system appeared to be more effective in settlement reduction compared to the open-end system (Figures 6a and 6b). However this deficiency of the open-end system was compensated with greater pipe lengths, as shown by the equal settlements of L75_34 and L75_51 in the same figures. The settlement reduction seemed slightly diminished with increased spacing of the pipes for the close-end system, but was quickly recovered with increased pipe lengths (Figure 7a). As for the open-end system, having the pipes further apart was clearly detrimental to this effect, causing up to almost 15 % of additional settlement (Figure 7b).

The observations above are indicative of the importance of compatibility between the pipe length and spacing in the foundation system, regardless of the pipe end conditions. For instance, if short pile lengths are preferred (due to availability of the cut-offs), an open-end system with greater spacing between the pipes is effective to bring settlement down by more than 50 %. Of course, the close-end system was apparently far less affected by the spacing between pipes, as the extra soil-base contact provided additional end resistance, enhancing its ‘floating’ capability.

4.2 Settlement Behaviour: Pipe Length and Spacing Effects

The settlement – vertical stress relationships for all samples from both systems can be found in Figures 8 and 9. Note that settlement was defined as the Settlement Ratio, i.e. the ratio of settlement (ΔL) per depth of the soil bed (H), while the vertical stress was obtained by simply dividing the load by the surface area of the foundation platform (i.e. 100 mm x 100 mm). These plots give more insights to the settlement control mechanism of each system, particularly with regards to the influence of pipe length and spacing respectively.

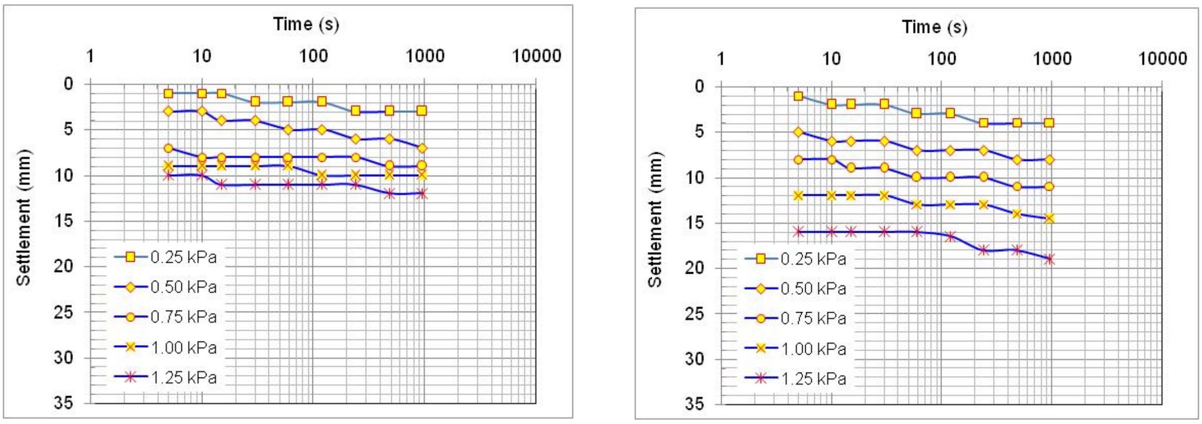
The close-end system fared well in both 34 mm and 51 pipe spacing arrangements by having less or equal settlements at every stress level compared to the Control sample (Figures 8a and 9a). The trend of these plots corresponds well with the discussion made earlier on the settlement rate, where neither the pipe length nor the spacing dominated the foundation’s performance in settlement control. Nevertheless the same cannot be said of the open-end system (Figures 8b and 9b). The open-end system with 34 mm pipe spacing suffered more significant settlements at the same stresses compared to the Control sample, though the 75 mm long pipes (i.e. sample L75_34, Figure 8b) did compensate for the lack of end bearing with greater frictional resistance by the longer pipes. On the other hand, the open-end 34 mm spacing system recorded the least settlement with the shortest pipes (i.e. 25 mm), while the longer pipe systems of 50 mm and 75 mm registered similar or worse subsidence with reference to the Control sample (Figure 9b).

The above observations point towards the dependency of the open-end system on the pile length to mobilize sufficient bearing capacity. A threshold of 75 mm length pipe is necessary, for instance, to carry imposed vertical load, even at a close spacing of approximately 1.6 times the diameter of the pipe (34 mm), centre-to-centre (Figure 9a). When spacing is increased to 2.32 times of the pipe diameter (51 mm), the longer pipes seemed to puncture the soft soil and induce excessive settlement in the foundation (Figure 9b). Shorter pipes allowed limited penetration as there was only so much internal space to accommodate the pushed-in soil, where the soil plug effectively sealed off the open ends at early stage of load application. The longer pipes, and hence larger cavities, would have permitted the soil plugs to rise higher into the pipes, resulting in more foundation subsidence. An illustration of the formation of soils plugs in the open-end system is given in Figure 10.

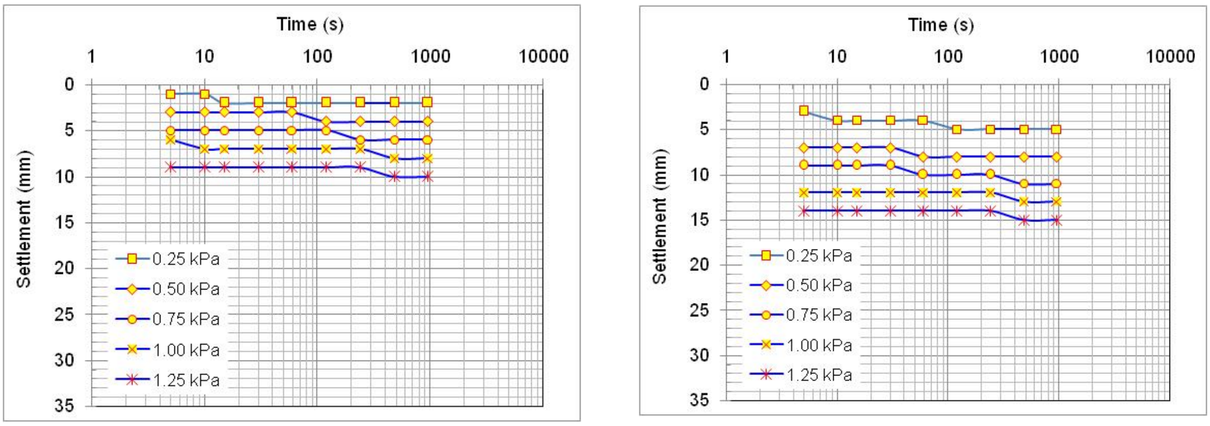
Figure 11 shows the correlation between Settlement Ratio and pipe spacing. As the effect of only two spacing distances were examined in this study, the data points, as expected, fall on two parallel columns in the plot. The close-end system clearly displayed better settlement control, registering ΔL/H of 0.05-0.08. The open-end system endured greater settlements, as is evident in the ΔL/H values that charted higher range, i.e. 0.06-0.10, except for L25_51. This exception matches the observations and discussions made in the previous paragraph with reference to Figures 9 and 10, which was attributed to the soil plug penetration depth effect.

The Young’s modulus (E) was derived by taking the settlement of the foundation systems at the final loading stage of 1.25 kPa, and plotting a linear regression line through the settlement data points and the origin. In the plot of Settlement Ratio (ΔL/H) versus E (Figure 12), it appeared that the stiffness of the foundation system is inversely related to the settlement, i.e. ΔL/H = 0.16/E. In other words, the stiffer a foundation is, the less settlement can be expected of it. Again, data points of the curve in Figure 12 correspond well with the settlement behaviour elaborated above.

L25_34



L50_34



L75 34

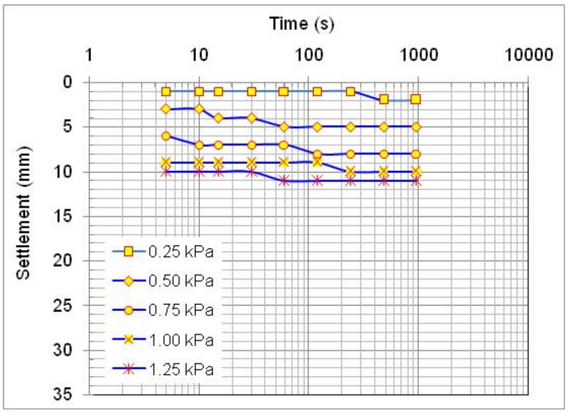


Figure 6a. Settlement plots (34 mm spacing; close-end system)

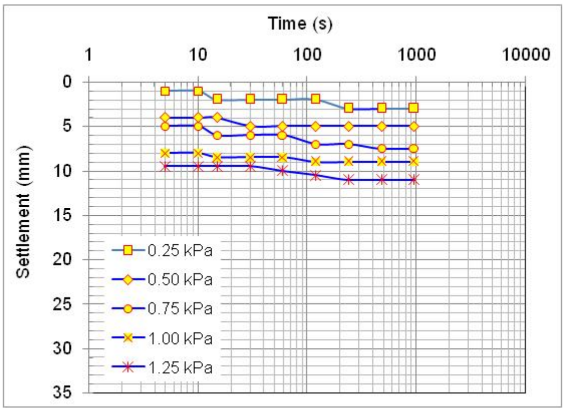
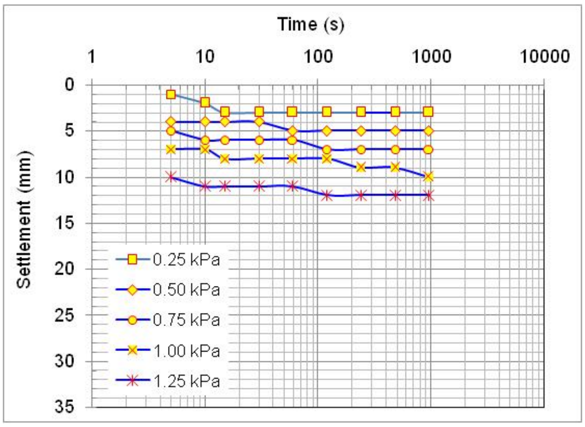
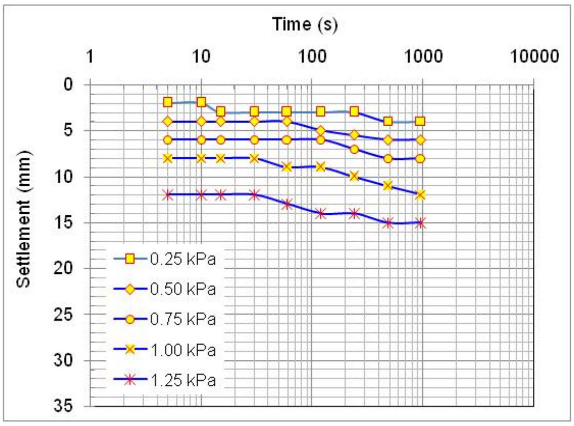


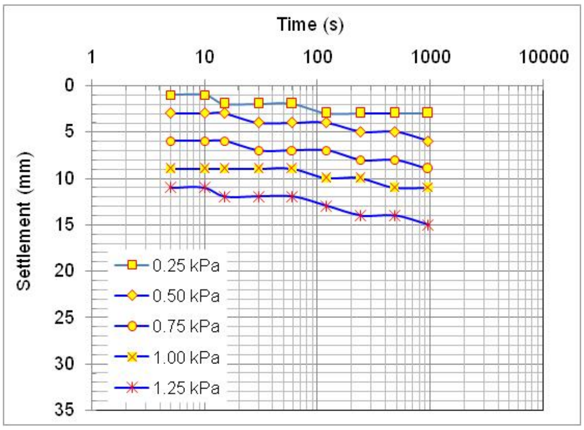
Figure 6b. Settlement plots (34 mm spacing; open-end system)

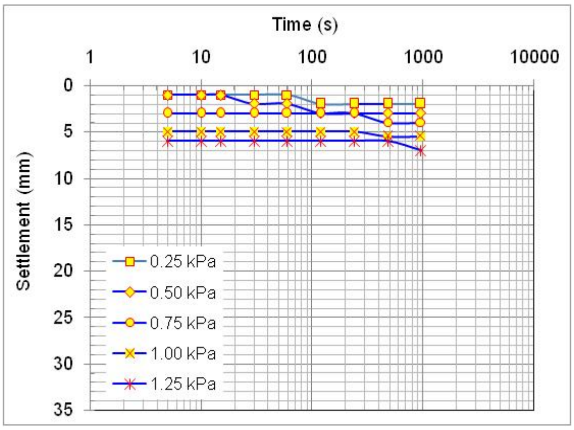
L25_51





L50_51





L75_51

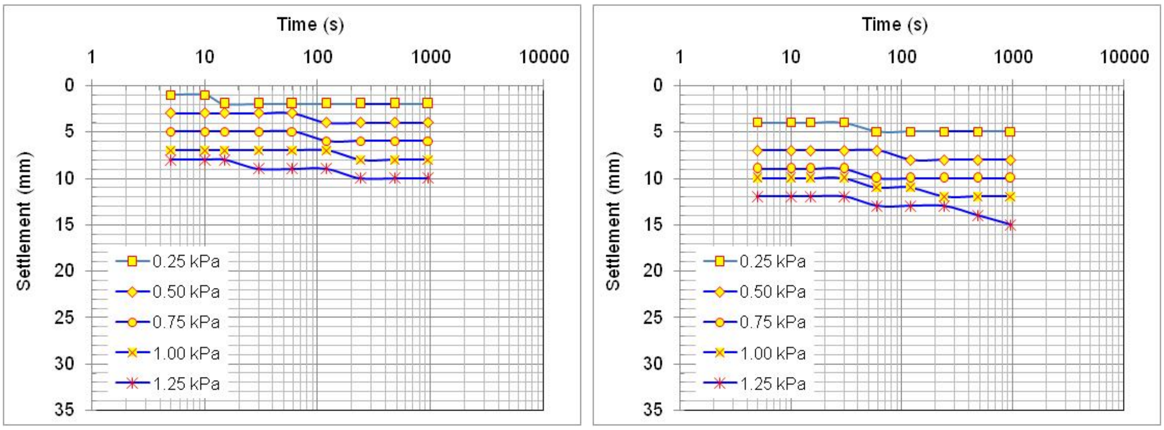
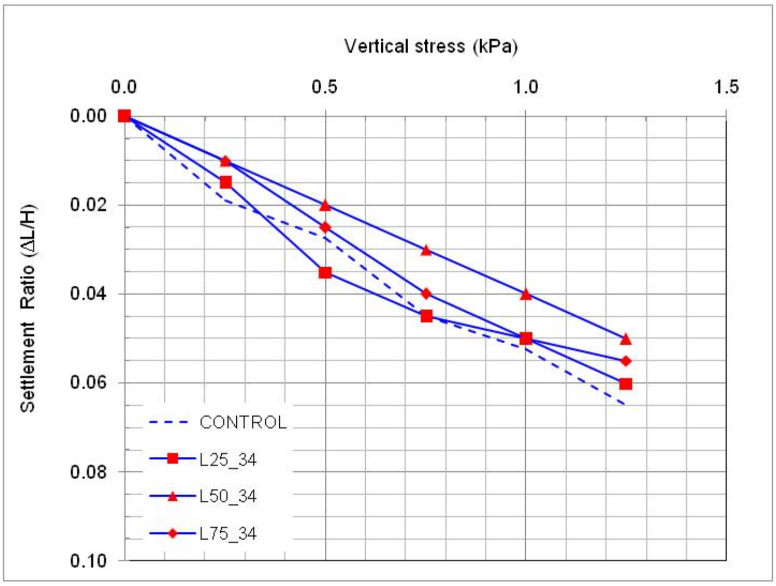


Figure 7a. Settlement plots (51 mm spacing; close-end system)

Figure 7b. Settlement plots (51 mm spacing; open-end system)

a. Close-end system



b. Open-end system

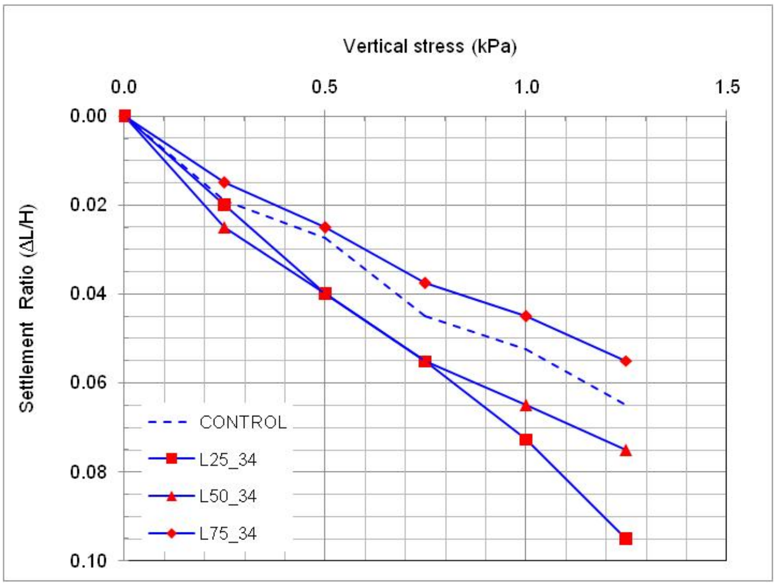
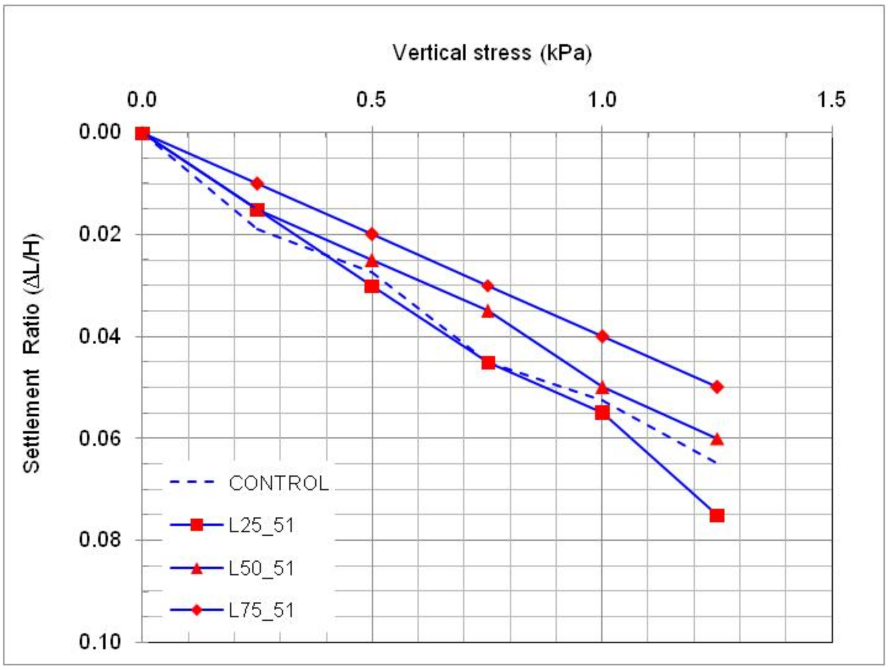


Figure 8. Settlement Ratio (ΔL/H) - vertical stress plots (34 mm spacing)

a. Close-end system



b. Open-end system

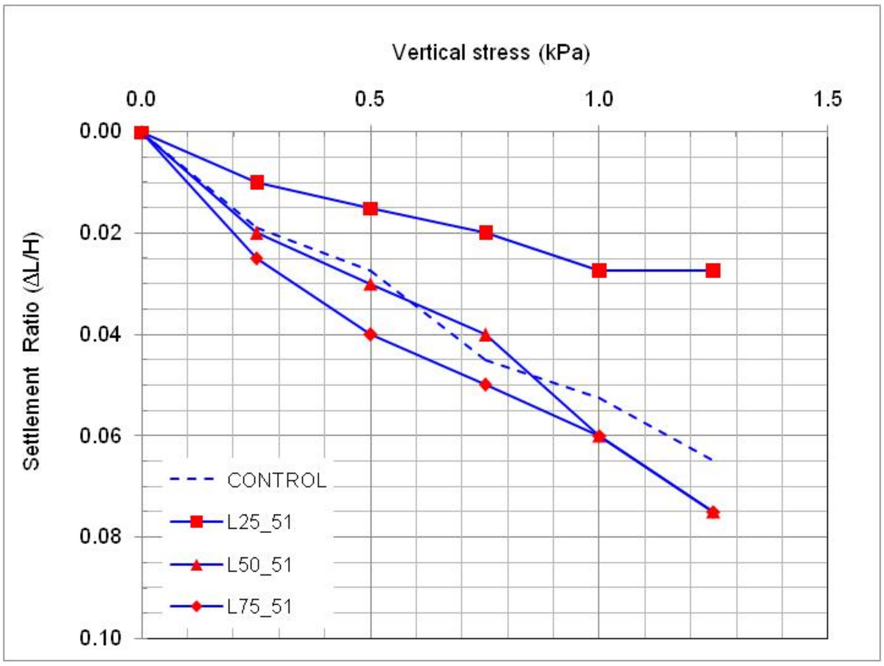
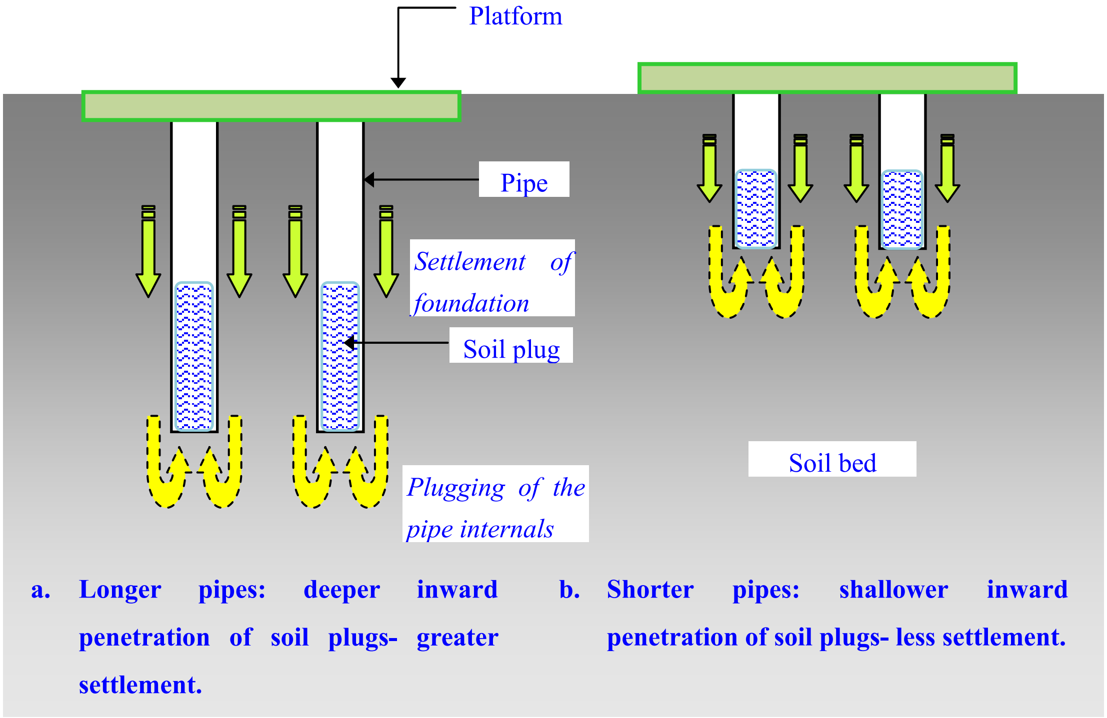


Figure 9. Settlement Ratio (ΔL/H) - vertical stress plots (51 mm spacing)



a. Longer pipes: deeper inward penetration of soil plugs- greater settlement.

b. Shorter pipes: shallower inward penetration of soil plugs- less settlement.

Figure 10. Formation of soil plugs in the open-end system

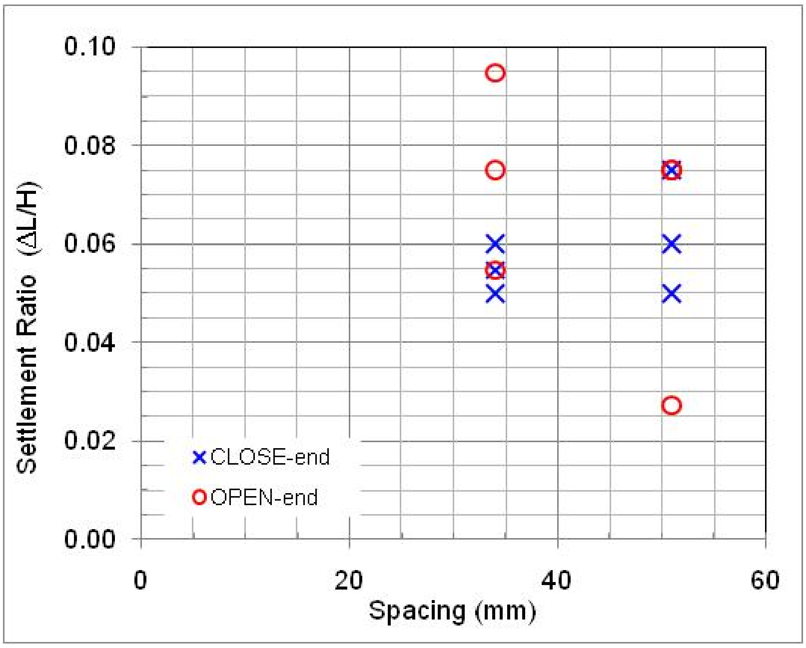


Figure 11. Settlement Ratio - spacing

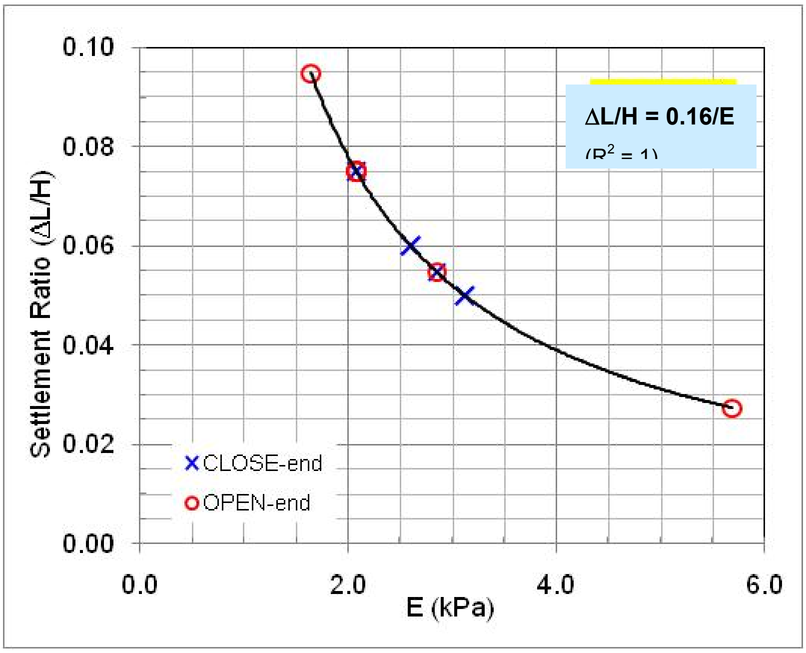


Figure 13. Settlement Ratio (ΔL/H) - Young's modulus (E)

5. Conclusions

- The *"Akar Foundation"* can effectively reduce settlement of structures built on soft soils, such as peat deposits, but due consideration must be given to the compatibility between the pipe length and spacing of the system.
- For the close-end system, end resistance provides most of the bearing capacity of the foundation.
- As for the open-end system, the penetration height of the soil plug can have significant effect on the resulting settlement control.
- The squeezing effect of adjacent pipes on the soil between them could effectively enhances the frictional resistance via over-lapping lateral pressure (effective pipe spacing), and hence provides better settlement control.
- Further work to the development of the *"Akar Foundation"* encompasses the examination of the surface roughness of the pipes for greater frictional resistance mobilization, and long term settlement monitoring under the intended design loads.

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