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A Shallow Foundation System for Buildings on Soft Soils

Chee-Ming Chan[1], Pik-Yen Wong[2] and Chai-Chin Lee[3]

[1,2&3]Research Centre for Soft Soils (RECESS), Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA. E-mail: [1]<chan@uthm.edu.my>, [2]<pikyen_1986@hotmail.com>, [3]<judith_lcc@hotmail.com>. Affliations: [1]Senior Lecturer/Research Fellow, [2&3]Research Student.

ABSTRACT

Development on weak soft grounds, which has so far been avoided, is fast becoming inevitable due to land scarcity with increased population and land use. To build on such soils either elaborate ground improvement work needs to be carried out prior to construction, or deep foundations need to be installed. These methods are not always economical, involving excessive machinery mobilization as well as resources and labour utilization. There is therefore a need to seek a more economical and sustainable solution, especially for development in rural areas that are rarely endowed with huge building funds. Based primarily on the principles of a floating foundation, a simple shallow foundation system was developed and the preliminary findings are presented in this paper. The *"Akar Foundation"*, which literally translates as "Root Foundation", is essentially a lightweight platform supported by a group of hollow stumps (i.e. PVC pipes) beneath.

BACKGROUND

Development favours sites with good quality soils: strong, stiff material that give minimal subsidence while carrying the loads imposed by the infrastructure build on it. Nevertheless this luxury is rapidly diminishing due to the increasing population and various land use projects that utilize these sites. From the perspective of rural development, the prospect is perhaps even grimmer as these are often economically-challenged places that are rarely given funding priority.

When encountered with such soft soils, like soft marine, alluvial and organic clays as well as peat (pure organic soils), some additional considerations are required in providing a sufficiently strong foundation to sustain the buildings 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. If these conditions are not met, buildings will eventually suffer structural deterioration due to non-uniform and excessive subsidence of the ground and worse still, face the risk of imminent or sudden collapse.

In Malaysia, peat and organic soils are considerably extensive. Mutallib et al. [1991] reported that these deposits represent some 8 %, which is equivalent to approximately 2.6 million hectares, of the total land area of the country. Organic soils in particular, have an inhomogeneous and anisotropic structure that differs greatly from inorganic soils, resulting in their peculiar engineering properties (Kallioglou *et al*., 2009), which are usually unfavourable for bearing load. These soils are commonly water-logged and contain high percentage of organic matters at different decomposed stage. The Malaysian peat, for instance, is usually located at sites with a high water level all year round, thus providing very limited resistance against loading and settlement in short or long term (Chan and Abu Talib, 2008). Even a moderate load can lead to a large change in volume in these soils (Huat, 2002), making them notoriously known among engineers as problematic soils.

The common foundation adopted for these areas are deep and dense piling. While the piles serve the purpose well by transferring the building 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 the optimal skin friction and end bearing.

For the construction of smaller structures, such as individual dwellings, Hadmodjo (1991) from Indonesia proposed the use of the locally termed *"Cakar Ayam"* or "Chicken Feet" foundation system. The system consisted of a reinforced concrete slab resting on a number of reinforced concrete pipes. 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. However the increased self-weight of the foundation, apart from the weight imposed by reinforced concrete slab and pipes, could have offset some effectiveness of the system itself when loaded.

***"AKAR FOUNDATION"*: ORIGIN AND DESIGN CONCEPT**

The origin and design concept of the *"Akar Foundation"* draws 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 "root of plants". 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, the wide-spread live tentacles of a tree inadvertently penetrate and grip the soil as they grow and expand, eventually developing a formidable foundation to support and uphold the main trunk and branches 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 "floating" of the entire foundation system. The root network concept resonates with that of the subground activity of live roots of trees and plants 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, limiting additional structural load on the soil by spreading it out 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' element to the system.

EXPERIMENTAL WORK

Test Setup

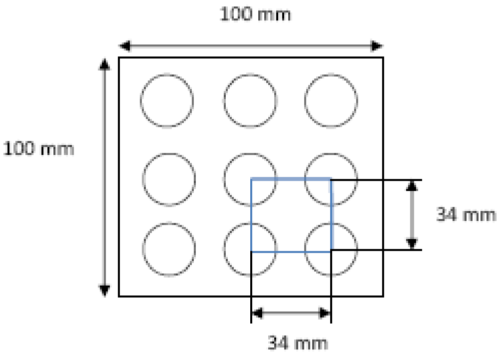


Figure 1. Arrangement of the PVC pipes in the foundation model.

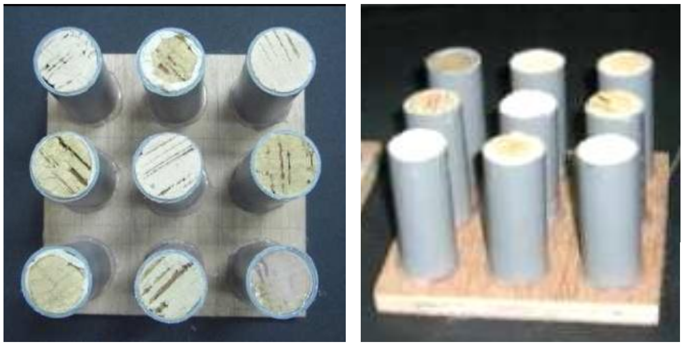


Figure 2. The miniature *"Akar Foundation"* model (close-end).

The miniature *"Akar Foundation"* foundation model was made of a piece of 100 mm x 100 mm x 20 mm thick plywood and PVC pipes of 22 mm external diameter and 15 mm internal diameter. The individual pipes, measuring 50 mm in length, were spaced equally at 34 mm centre-to-centre and glued to the bottom of the plywood (Figure 1). A pair of models were prepared, one with open-end pipes (Wong, 2009) and the other with close-end ones (Lee, 2009). 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.

The load test was simulated in a glass cube chamber of 300 mm x 300 mm x 300 mm. A peat sample collected from the Melaka state 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	
Peat type	Sapric	

Figure 3. Remoulded soil left to cure overnight.

Figure 4. Preparation of the soil bed.

The soil sample was first remoulded in a separate tank, 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.

The mass of the soil bed was kept constant at 40 kg, where it was formed 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. 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 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 4). The final settlement of the foundation under each load was recorded at a fixed time lapse of 16 minutes. A control test was also included in the test programme, with only the plywood platform placed on the soil bed and loaded accordingly.

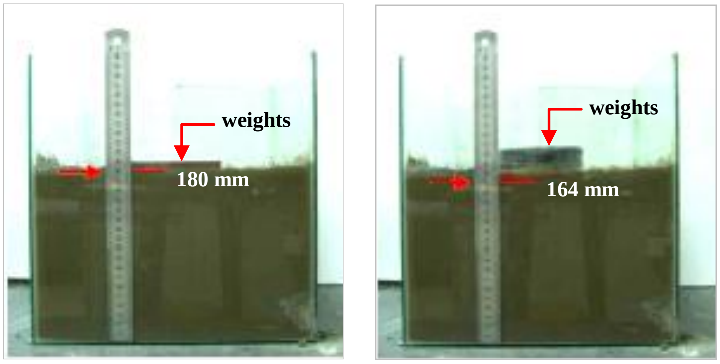


Figure 5. Load test of the foundation system: the arrow marker indicates the soil bed level (settlement) under different loads.

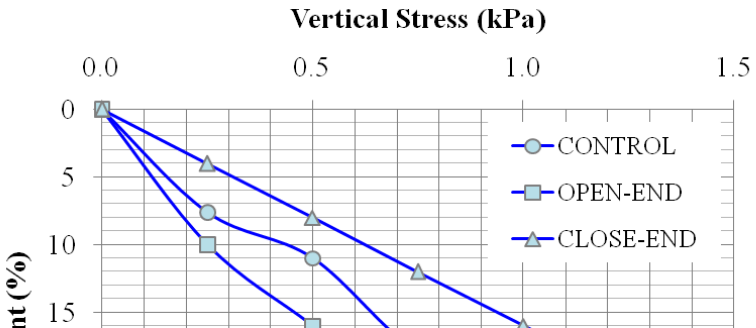
Results: Analysis and Discussions

Looking at the settlement-vertical stress plots for all three test conditions, i.e. control, open-end and close-end pipe systems (Figure 6), it is immediately obvious that the open-end system settled the most (15 mm, corresponding to 30 % per length of the pipes). The control test, which represented a flat plate loading test, gave the second most settlement. In comparison, the close-end system effectively reduced the total settlement by 6 % with reference to the control system.

Figure 7 illustrates the settlement ratio derived from division of the settlement with the depth of the soil bed, i.e. 200 mm. Note that the seemingly scattered control test data was most likely due to experimental errors and other limitations of the test setup, such as uneven settlement of the plywood platform during test. The plot was smoothened out by fitting a linear regression line (correlation factor, R^2=0.98) through the data points, as depicted by the dashed line in Figure 7. With this correction, both the plots of the control and close-end systems show linear increment of the settlement ratio. The same cannot be said of the open-end system, where the initial convex curve suggests significant settlement upon loading.

This observation points to the possibility of the formation of a soil plug that sealed off the open ends at the initial loading stage. Hypothetically, the edge of the pipe end cut through the soft material as the open-end pipes were pushed into the soil bed. Further penetration of the pipes forced the detached soil bulks into the cavity of the pipes, displacing air within the internal space. Next, with the soil plug sealing the ends, the foundation system began to behave more like a close-end system. Nevertheless higher loads could have pushed the soil plug further up the pipe cavity, resulting in extra settlement as shown in the curved plot of the open-end system in Figures 6 and 7.

Stiffness-wise, the close-end system gave a Young's modulus of 6.3 kPa, 1.5 times that of the open-end system (4.2 kPa), and 1.3 times greater than that of the control system (4.8 kPa).



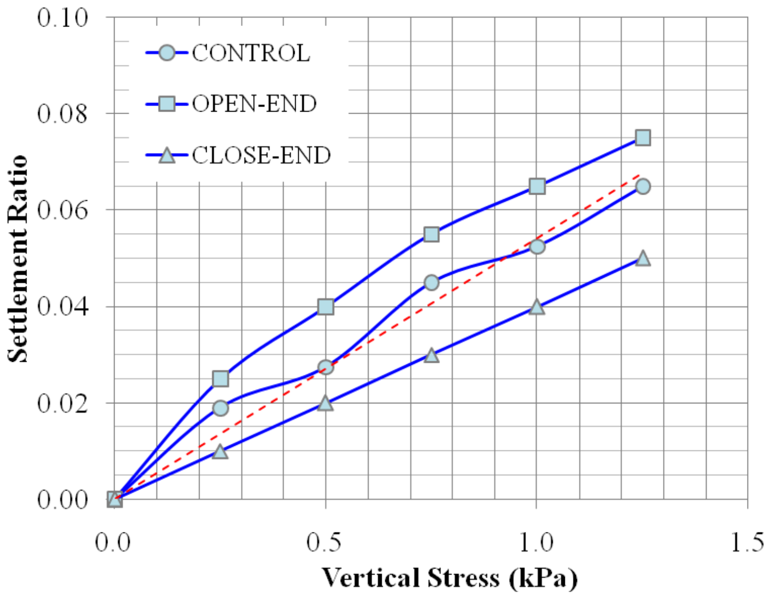


Figure 7. Settlement ratio plots.

The stiffness estimation was based on the total settlement recorded in the final loading stage. The stiffness of the close-end system is in accordance with the reduced settlement, lending further to its potential for carrying and distributing loads as an effective shallow foundation.

CONCLUSIONS

a. The *"Akar Foundation"* can effectively reduce settlement of structures built on soft soils, such as peat deposits.
b. The close-end system gave better settlement control compared to the open-end ones.
c. Referring to (b), it is indicative that the end resistance of the foundation system plays a more critical role than the pipe internal skin friction. This can be further examined by varying the pipe internal wall roughness.

d. In order to enhance the external frictional component of the system, the spacing and length of the pipes may be varied and examined *(already in the pipeline at the time of writing)*.

e. It is also thought that the squeezing effect of adjacent pipes on the soil between them could effectively enhance the frictional resistance (via over-lapping lateral pressure), and hence provides better settlement control.

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