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GEOTECHNICAL CHALLENGES ON SOFT GROUND

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Abstract — Developments and constructions on soft ground pose great challenges in the field of geotechnical engineering. Although soft ground is no longer considered a new concern in developments and constructions; there are many issues that may crop up repeatedly if proper planning, analysis, design, construction control and supervision are not implemented. This paper presents the common challenges faced on soft ground and aims to provide some insights on good design and construction practices. The suggestions provided in this paper are collection of experience gained from various projects.

***Keywords*:** soft ground, soft soil

1.0 INTRODUCTION

It is commonly for developments and constructions in Malaysia to encounter soft ground. Differential settlement, excessive settlement and long-term settlement are the main issues for constructions over soft ground [1–3]. Despite these well-known issues on soft grounds; there are still repeated failures that can be mitigated if proper planning, analysis, design, construction control and supervision are implemented. This paper presents the common issues faced on soft ground and aims to provide some insights on good design and construction practices in tackling geotechnical challenges over soft ground.

2.0 COMMON ISSUES ON SOFT GROUND

2.1. Differential Settlement of Piled and Unpiled Area

A common overlooked design, particularly in soft ground, is for the building to be supported by piles while the area without building such as the car porch area is not supported by piles because not much load will be imposed on the car porch area compared to building structures. However, the additional weight of the car porch slab or if there is a filled soil layer over the soft ground at the car porch area will amplify the consolidation settlement, thus inducing differential settlement. See Figure 1 for examples of differential settlement of piled and unpiled areas.

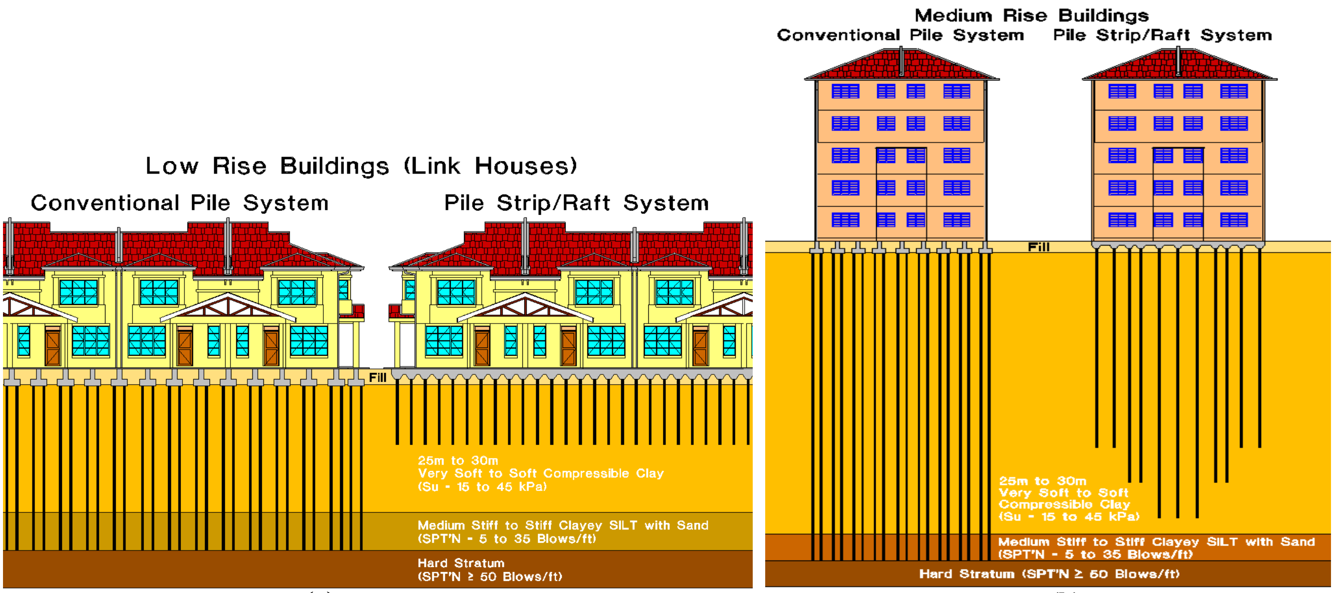
Figure 1 Examples of differential settlement of piled and unpiled area.

2.2. Piled Foundation with Surrounding Ground Settlement

Buildings on soft ground are often supported by piles and transmitted to the competent stratum, terminating in the hard layer or typically known as “pile to set”. If the surrounding soft ground with earth fill is not treated, primary and secondary consolidation settlements of the surrounding soft ground will take place. In those cases, such settlement of the soft ground can cause downdrag, resulting in a significant reduction of the pile working capacity and can cause failure to the supported building structures. There may also be long-term serviceability problems where the surrounding platform of the building can detach from the building, forming voids and exposing underground services and piles. This could lead to health and safety hazards, see Figure 2.

Figure 2 Settlement of platform over soft ground and detachment from building with piled foundation

Suggested solution for items 2.1 and 2.2, if there is a thick, soft compressible subsoil, the building foundation can be designed to settle together with the surrounding soft ground to mitigate the detachment of settling platform from a building (differential settlement should be checked and considered in design). Innovative foundation system, such as the “Floating” pile raft foundation can be used as proposed by [1, 2]. This system is also cost-effective compared to conventional piled foundations. Figure 3a shows the comparison of conventional pile system and the pile raft foundation for low rise buildings. A similar solution can be applied to medium-rise buildings, where the pile lengths of the piled raft foundation can be varied in order to reduce the differential settlement as shown in Figure 3b.



(a) (b)

Figure 3 Comparison of conventional and the “Floating” piled strip-raft foundation system.

2.3. Failure of Embankment

Failure of embankments typically occur during construction; Figure 4 shows an example of an embankment failure [3]. These failures are commonly caused by inadequacies in settlement and stability analyses of embankments. Embankment stabilisation methods such as basal reinforcements, surcharging with perforated vertical drains (PVD), piled embankments, etc. are often used to stabilise the construction of embankments over soft ground. However, if the designer fails to carry out proper investigations and analyses, embankment failure can occur. Liew et al. [4] pointed out that strain incompatibility between the basal reinforcement and embankment fill could cause embankment cracking and instability. As for piled embankments, weak lateral resistance of piles in supporting heavy vertical loading can often be overlooked in the conventional design. Contrasts between vertical resistance and lateral resistance of concrete piles and the inherent weak lateral pile resistance can easily lead to poor robustness of foundation design [5].

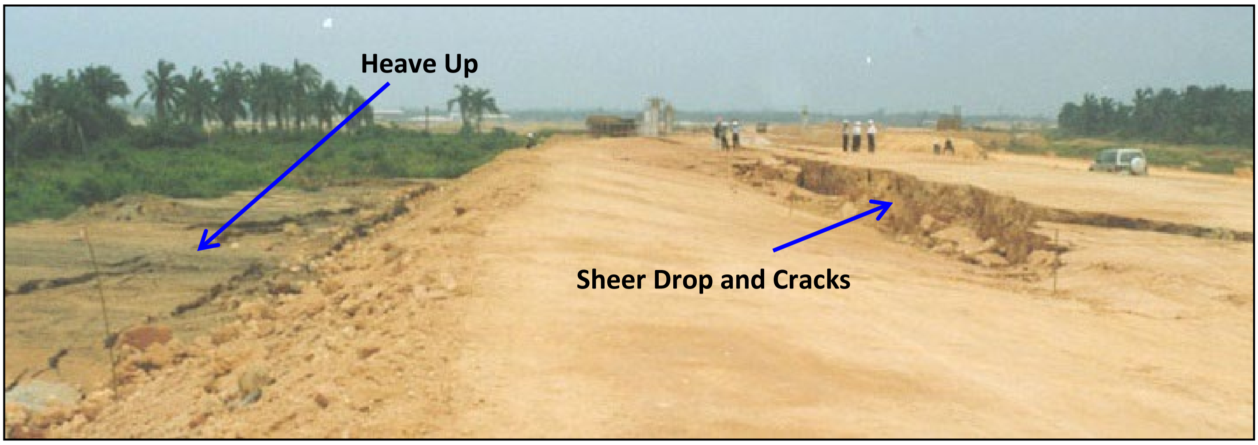


Figure 4 Failure of an Embankment [3]

Suggested solution:

It is important to be aware of any specific project requirements in terms of serviceability criteria (deformation, tolerances, bearing capacity, etc.), costs, site constraints and time. Subsoil conditions and information need to be thoroughly investigated before proper geotechnical design is carried out in order to control embankment settlement and deformation and also address the stability of the embankment. Counterweight berms on embankment sides can be used to enhance the stability of embankments. Raked piles with lateral self-balancing pile arrangement can be used to improve its robustness in taking lateral loadings. Reference [6] provides detailed design and construction control for embankment over soft clay.

2.4. Failure of Bridge Foundations and Approaches to Bridges

Significant differential settlement at bridge approaches are still common along highways and expressways in Malaysia. Bridge abutments over soft deposits are normally supported by piles. The piles for the abutment are usually installed to a firm/hard layer. The long-term settlement of the abutment is hence negligible. Reference [7] highlighted that the embankment adjacent to the abutment would still have some settlement with time. Consequently, this will create a significant differential settlement between a bridge abutment and flexible embankment as shown in Figure 5. For such condition, users will experience an unpleasant "hump" while driving over a bridge abutment.

Figure 6 shows a schematic diagram of another type of bridge foundation failure over soft ground, a slip failure of bridge foundation and the approach to a bridge[8]. Such failure is deep-seated and due to the weak subsoil which is unable to support the weight of the approach embankment. It is a common misconception that as long as the structural design of an abutment has taken into consideration both vertical and lateral pressures, slip failure will not occur. However, the weight of the embankment can initiate the consolidation settlement of the soft subsoil and induce its failure. In addition, the deep-seated instability of the embankment fill over thick soft ground behind the abutment can seriously affect the stability of an abutment.

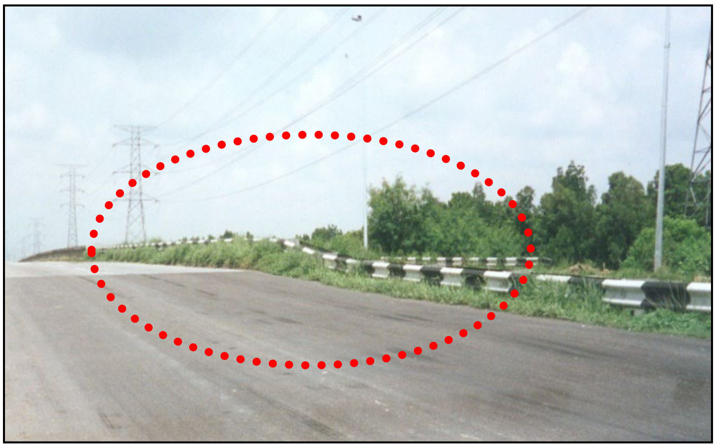


Figure 5 Hump at bridge approach

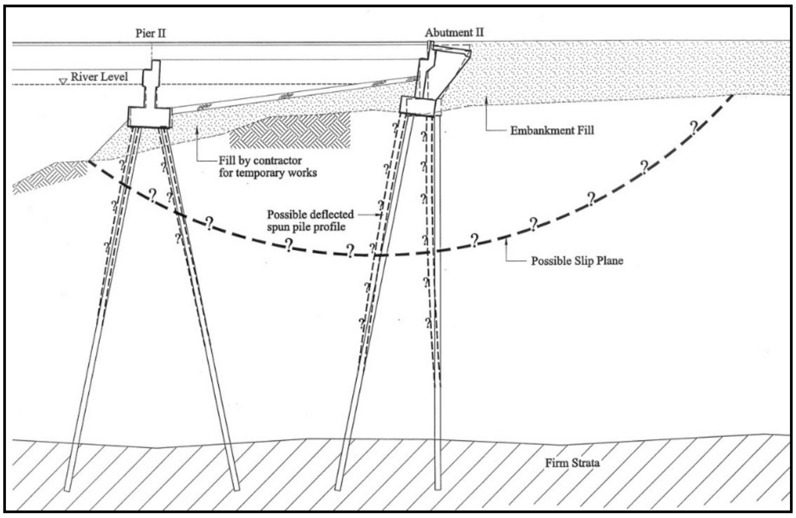
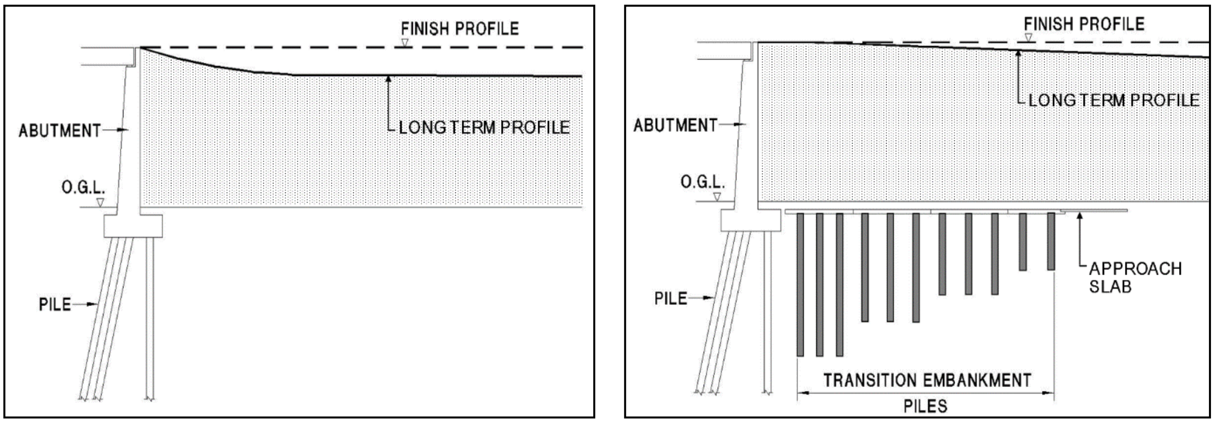


Figure 6 Schematic of slip failure of bridge foundation and the approach to a bridge [8]



(a) **(b)**

Figure 7 Settlement profile at bridge approach, without (a) and with (b) transition piles [7]

Suggested solution:

To minimise the differential settlement between a bridge abutment and the flexible embankment, piled embankments with different pile lengths as transition area can be utilised to provide a smooth profile between the bridge abutment (rigid structure with pile to set) and embankment. Figure 7 shows the settlement profile at bridge approach with and without transition piles to illustrate the solution to mitigating differential settlement [7].

It is important to check the stability of the embankment on the possible failure modes. It is also important to be aware of lateral soil pressure imposed on piles by the embankment fill behind an abutment to prevent failure of piles supporting the abutment. Failure can be avoided if proper geotechnical designs are carried out, with the understanding of the subsoil condition and the awareness on the possible problems.

2.5. Undulating Surface "Mushrooms" Over Soft Ground

It is common to encounter undulating surface "mushrooms" along an expressway over soft ground. Figure 8 shows an example of "mushrooms" on an expressway [9]. Such problem is mainly due to piled embankments on individual pile-caps over soft compressible subsoil. The design principle relies on the arching mechanism of the embankment fill materials to transfer the loads to individual pile-caps. However, the differential settlement on the expressway forms "mushrooms"; indicating that the arching mechanism is ineffective due to the thin fill layer above the pile-caps.

Figure 8 "Mushroom" Undulating surface on an expressway (Modified after [9])

Suggested solution:

Individual pile-caps for embankment over soft ground should be avoided, unless proper fill and adequate thickness for soil arching to take place. Proper ground treatment should be carried out for the soft ground before construction. For the case of existing "mushrooms", an innovative method of using RC raft at shallow depth as described in [9] can be used to remedy such problems.

2.6. Excessive Settlement Surrounding Piled Utilities

Utilities are often important infrastructures that can be sensitive to settlement, particularly differential settlement. A basic instinct for many engineers is to support the utilities using piles over soft ground. If the utilities are supported by piles to the competent stratum (hard layer), the utilities will not suffer from damages due to settlement of the soft ground. However, such design is counter-intuitive, particularly if the surrounding soft ground is not treated properly, as it will settle over time, inducing cracks and humps on the surface of the piled utilities, as shown in Figure 9. Typical remedial works regarding such issues are to backfill and resurface the area. However, backfilling over soft compressible ground is actually adding weight onto the soft ground and will induce further consolidation settlement of the soft compressible ground, subsequently leading to perpetual formation of differential settlement over the utility.

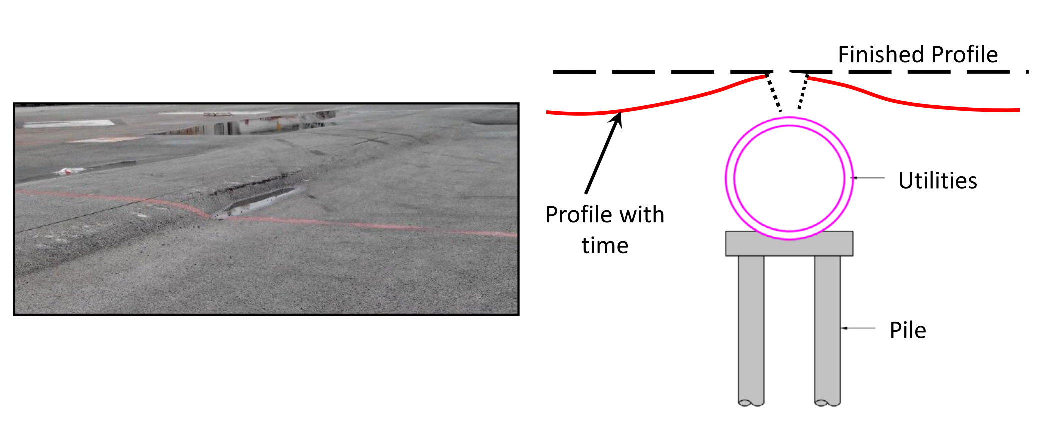


Figure 9 Humps and cracks on the piled utilities over soft ground

Suggested solution:

Proper ground treatment needs to be carried out before laying the utilities over soft ground. Pile foundations on utilities should be avoided, particularly when dealing with soft compressible ground.

2.7. Inadequate Ground Treatment

Another common issue on soft ground is inadequate ground treatment. A typical ground treatment for soft ground is to provide surcharging coupled with PVD. Such ground treatment aims to accelerate the consolidation process to achieve the desired degree of consolidation. The surcharge will then be removed after a "waiting period", once the soft ground has achieved the desired degree of consolidation. It is not unusual to encounter failures of such ground treatment, mainly due to inadequate "waiting periods", where the soft ground has not yet achieved the desired degree of consolidation. This means that the soft ground will continue to settle over time.

Suggested solution:

It is important for all parties to understand the importance of the "waiting period" in such ground treatment methods, such as surcharging. If the construction time does not permit the required "waiting period", a different ground treatment method should be carried out instead.

3.0 GOOD DESIGN PRACTICE

3.1. Proper Subsurface Investigation

The unforeseen costs associated with construction on soft clay are geotechnical in nature and the additional costs are often attributed to inadequate planning of subsurface investigation and improper interpretation of the factual information and results of field and laboratory tests [10]. Therefore, planning of the subsurface investigation is crucial [10] provides a comprehensive guide on the planning of subsurface investigation and interpretation of test results for foundation design in soft clay.

Table 1 shows some of the typical important parameters when dealing with soft soils and the tests required to obtain these parameters. Basic soil classifications parameters are not shown in Table 1 such as: moisture content, Atterberg's Limits, unit weight, specific gravity, particle size distribution, etc., Standard Penetration Test (SPT) and effective stress profile are also essential.

Table 1 Some Important Parameters for Soft Soils

Parameters	Field Tests	Laboratory Tests	Remarks
Undrained Shear Strength (s_u)	Cone Penetrometer (Piezometer) with Pore pressure measurements (CPTU), Field Vane Shear	Triaxial (CIU, UU), Laboratory Vane, Shear Box	For stability and bearing capacity check
Ground Water Level	Standpipe, Piezometer	-	-
Consolidation Parameters, p_c', OCR, C_v, C_C, C_R, C_α m_v	-	Oedometer	To estimate consolidation settlement and deformation
Permeability, k	Pecker test	Constant head, Falling head	To estimate rate of settlement

3.2. Avoid or Minimise Fill on Soft Ground

One of the greatest culprits in soft ground issues is the additional fill on top of an existing soft compressible ground. The additional fill over soft compressible ground adds weight onto the soft ground which will induce further consolidation settlement of the soft compressible ground. Therefore, one should try to avoid or minimise fill on soft ground. Sub-basements can be introduced to minimise fill. Proper geotechnical analyses and designs need to be carried out and the understanding of the subsoil conditions as well as the awareness on possible problems of additional fill on soft compressible ground are essential.

3.3. Considerations for Ground Treatment

The most common problem faced by engineers regarding soft ground is whether ground improvement is needed and the types of ground improvements to be carried out. The following factors should be taken into consideration when making a decision:

- Geological and geotechnical information of the site
- Type of structures to be constructed and the movement tolerances of the proposed development
- Time and duration allocated for the construction
- Construction costs and future maintenance costs

3.4. Floating Foundation

Conventional piled foundation aims to provide adequate load carrying capacity and to limit overall settlement. Such piles are typically installed into competent stratum, where the solution only addresses the short-term load carrying capacity. However, the application of such pile foundation system can be seriously affected by the underlying soft compressible soil, where pile capacity can be significantly reduced due to negative skin friction and also some long-term serviceability issues. As mentioned in Section 2.2, floating piled raft foundation can be useful in supporting buildings on soft ground. Some good examples of floating foundation which provide value-engineering solutions can be found in [11] and [12]. Floating foundations can be designed using skin-friction piles of different lengths by considering the interaction between piled raft and soil in order to produce an optimum design that satisfies both serviceability and ultimate limit states. Figure 10 shows a schematic example of a piled raft foundation system with varying pile lengths; the detailed design methodologies can be found in [12].

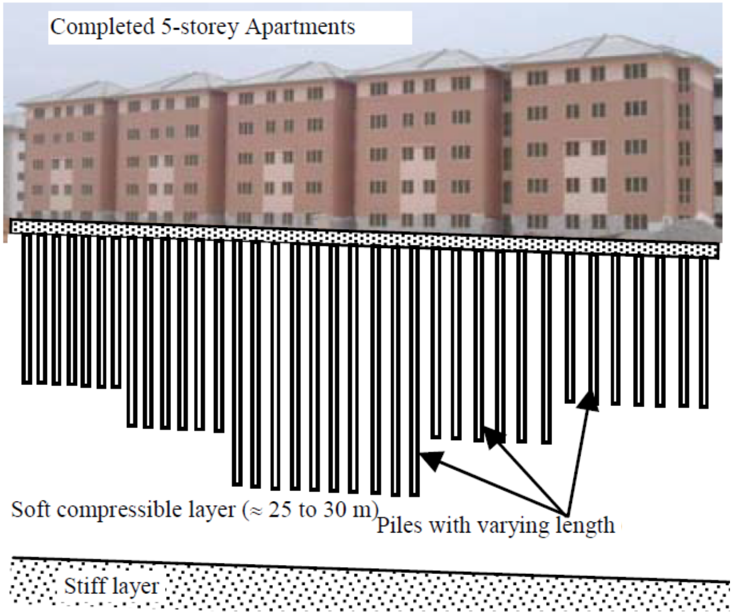


Figure 10 Schematic example of piled raft foundation system with varying pile lengths [12]

3.5. Importance in Detailing

Apart from proper geotechnical analyses and designs, detailing in design is equally important. For example, one of the important aspects in PVD construction is the water discharge outlet, which is often overlooked. Tan et al. [13] stresses that if the discharge outlet is clogged, the excess pore water will not be discharged effectively and will lead to a prolonged surcharge period. Some good practices in improving the PVD's efficiency include laying PVDs in a horizontal direction to further enhance the discharge of water and provide crusher run at the end of the sand blanket layer as shown in Figure 11. This is to ensure that there is a clear outlet for water to exit the subsoil through vertical drains and subsequently be discharged from the treated embankment efficiently. Figure 11 also shows a clear, visible crusher run layer that can facilitate easy inspection by supervising engineers and also helps prevent contractors from accidentally blocking the discharge outlet.

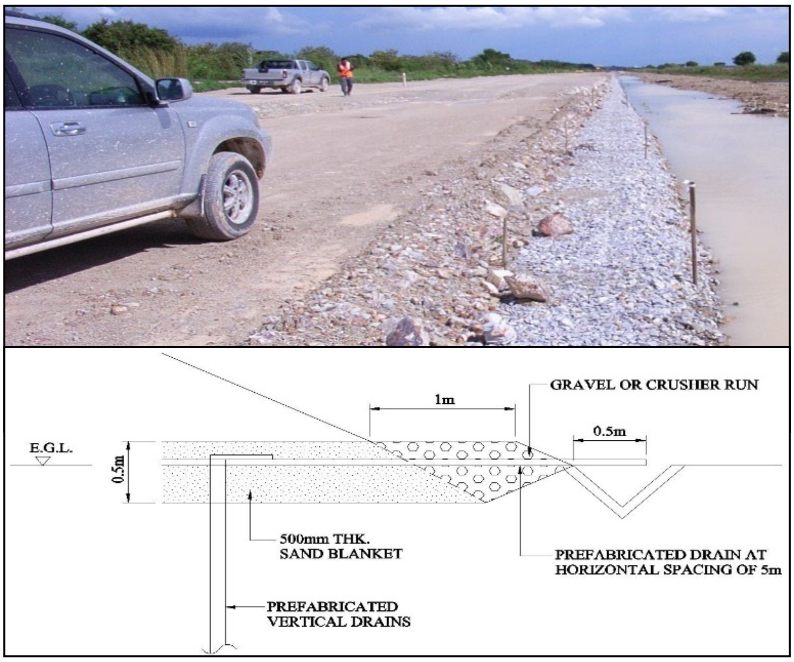


Figure 11 Detailing of water discharge outlet for PVD treatment [13]

3.6. Communications With Clients and Owners

Although experienced geotechnical engineers can come up with value-engineering solutions; they are often faced with dilemmas in providing optimum solutions that can meet with the clients' or owners' budget and construction time frame. It is inevitable that time and cost play a major role in all constructions and developments. Nevertheless, the safety and long-term performance of an engineered system has to be upheld. Geotechnical engineers should always communicate the importance of their designed systems to their clients and owners. For example, they should highlight the required time for ground treatment in order to achieve the required design level, etc. It is good to showcase some examples of failure where additional and unforeseen costs in construction resulting from a lack of proper geotechnical designs and lack of time for the needed construction period. This often helps to emphasize the importance of certain key design aspects and the necessity of a particular construction time frame.

4.0 GOOD CONSTRUCTION PRACTICES

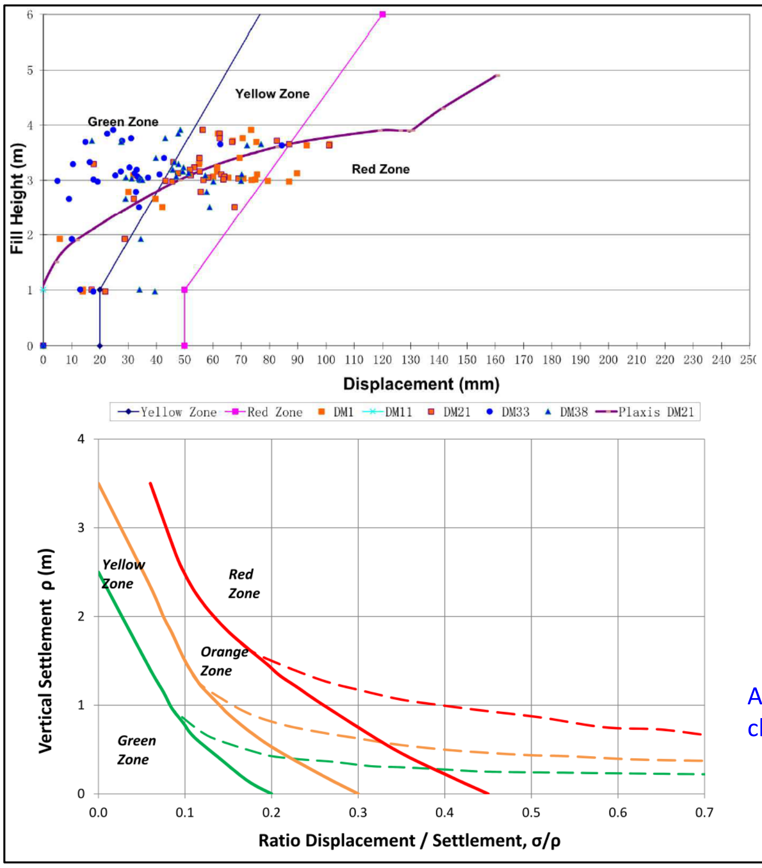
4.1. Construction Control & Monitoring

To achieve cost-effective constructions and developments in soft ground, aside from value-engineering designs, construction control and monitoring during construction are crucial. It is important to monitor the performance of a design during construction. Various instrumentations can be utilised in construction over soft ground. Table 2 shows the typical instrumentations used in soft ground constructions.

Table 2 Typical instrumentations used in soft ground constructions

Instrument	Measurement
Extensometer	Vertical movement
Inclinometer	Horizontal and lateral movement
Displacement marker	Vertical or horizontal movement on surface
Piezometer	Groundwater level and pore pressure

Tan and Gue [14] provides an overview of the design and construction control of embankment over soft cohesive soils; they also highlighted that careful and proper monitoring of the performance of an embankment during and after construction via instrumentation schemes are essential. Site-specific construction control charts can be developed and used as part of an early warning system to ensure and monitor safe construction over soft ground. Action plans can then be developed to prompt various relevant personnel during construction. This practice is supported by Tan et al. [15] through a case study where the authors demonstrated that such charts can be developed to assist in the surveillance of construction of soft ground embankments. They show that the combination of a construction control chart comprising embankment fill height versus lateral displacement, together with "Modified" Matsuo stability chart [16] and construction monitoring results can provide useful information to act as an early warning system on the performance of the ground treatment. Figure 12 shows an example of the site-specific construction control chart and the respective alert action levels should the actual performance during the construction require any specific attention or action. It is important to note that Figure 12 is only an example of a site-specific calibrated construction control chart and not a general construction control chart which should not be used on any other project site.



Zone	Action
Green	Embankment filling can continue.
Yellow	Supervising Engineer to inform design office and embankment filling can continue. For area with PVD, the embankment filling rate reduced to 0.5m/week.
Orange	Supervising Engineer to inform design office immediately. Embankment filling work only can proceed with permission from the design office
Red	Supervising Engineer to stop the embankment filling immediately and inform design office. Design office to review instrumentation data and advise on next course of action.

An example of a site specific construction control chart for embankment construction on soft ground

Figure 12 Example of a site-specific construction control chart and the alert action levels (Modified after [15])

4.2. Construction Sequence

It is important to note that failure can still occur during construction over soft ground, even with a proper design, because of a wrong construction sequence. Liew et al. [17] shows that sequence of pile installation in soft ground may cause undesired pile deviation. Figure 13 shows a wrong construction sequence of an embankment (modified after [18]). The counterweight berm is constructed after filling up to the surcharge level. The counterweight berm in such a sequence does not serve its purpose of improving the stability of the embankment. This construction sequence is not only wrong but also dangerous, particularly in constructing an embankment over soft ground, where the stability of the embankment is crucial when adding more weight from the surcharge onto the soft ground, as the embankment will fail before adding the counterweight berm. Before the soft ground gains in strength from surcharging, the embankment can be supported by the counterweight berm first before filling up to the required surcharge level as shown in Figure 14. To mitigate such issues in construction, it is essential to highlight the crucial construction sequence in construction drawings.

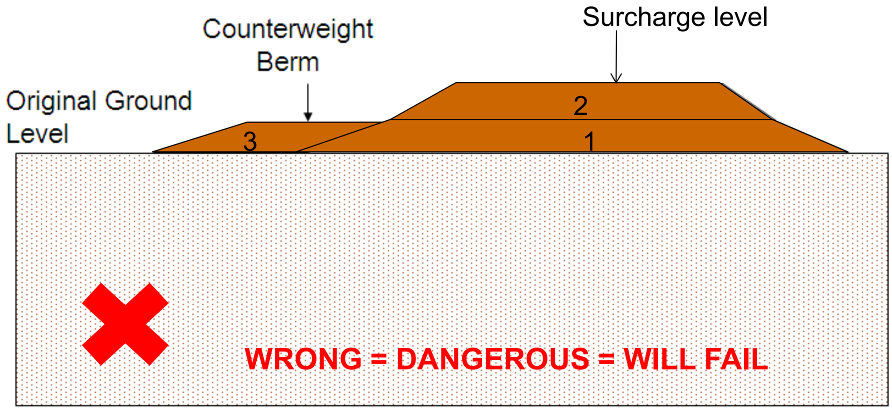


Figure 13 Wrong construction sequence of an embankment (Modified after [18]).

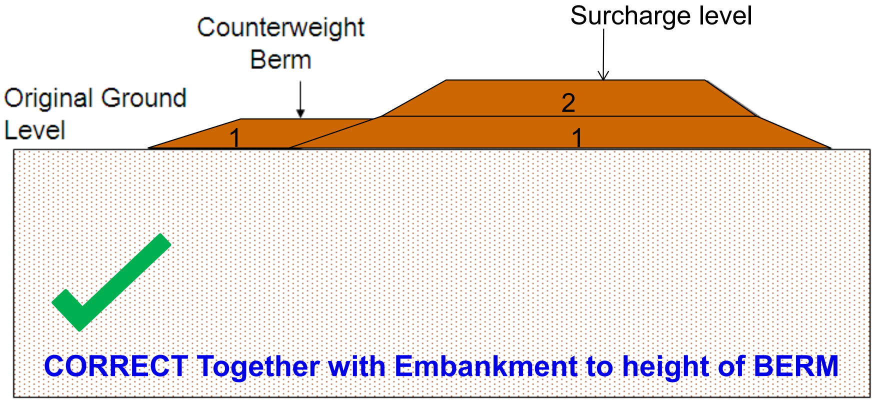


Figure 14 Correct construction sequence of an embankment (Modified after [17]).

4.3. Construction Supervision

Construction supervision plays a key role in preventing mishaps in construction. Supervision of construction activities are required to prevent unsafe practices and ensure adherence to safe construction practices. Some minor details if not identified and taken care of during construction, may lead to failure. Below are some examples of some typical overlooks in construction over soft ground:

- Improper storage of geotextiles (e.g., basal reinforcement); storage of geotextiles without proper cover will be exposed to sunlight prior to installation, which will affect the strength and durability of the geotextiles. Therefore, proper cover (e.g., cover with plastic sheet) and storage of geotextiles are essential to prevent exposure to sunlight prior to installation. Figures 15a and 15b show the incorrect storage and proper storage of geotextile respectively.

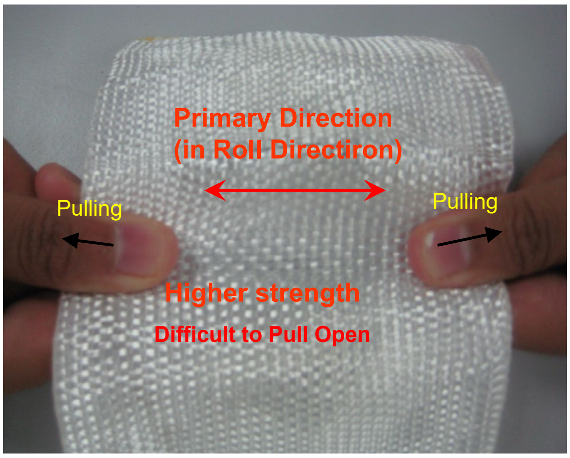
(a)

(b)

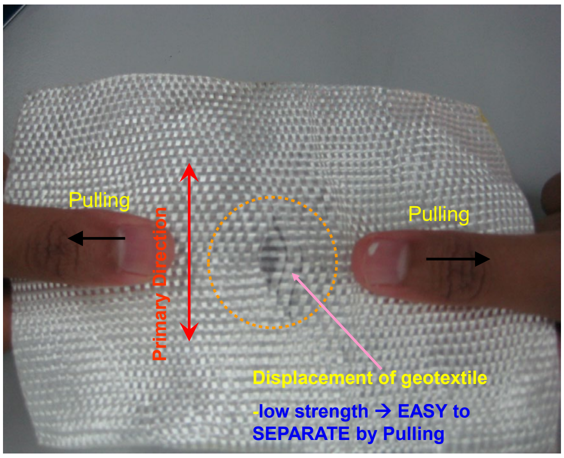
Figure 15 Improper (a) and proper (b) storage of geotextile at site (Modified after [18]).

- It is important to note and recognise that the design tensile reinforcement capacity of a geotextile basal reinforcement is in one principal direction. Figure 16 shows the difference in strength of a geotextile when pulling from different directions. The geotextile basal reinforcement should be laid on an embankment perpendicular to the primary direction of the geotextile basal reinforcement as shown in Figure 17.

In order for proper construction supervision to be carried out, comprehensive construction checklists are essential to ensure crucial details are not missed, thus mitigating any issues regarding overlooks.



(a)



(b)

Figure 16 Pulling a geotextile at the primary (a) and secondary (b) direction (Modified after [18]).

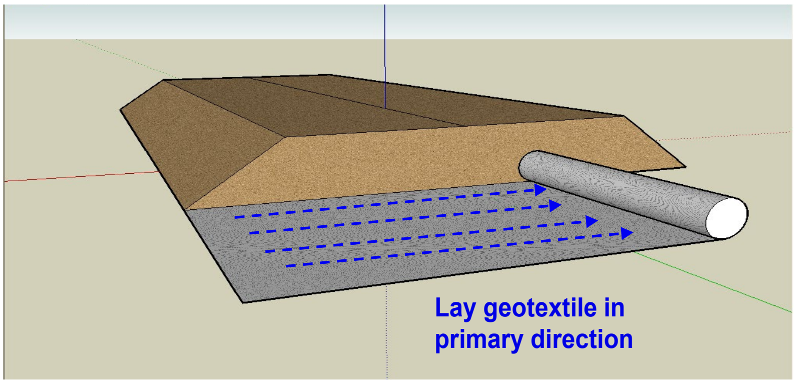


Figure 17 Geotextile basal reinforcement lay in the primary direction, perpendicular to the embankment (Modified after [18]).

5.0 SUMMARY

Common issues over soft ground can be mitigated as per the suggested solutions provided in this paper. It is vital to carry out proper and adequate subsurface investigation, interpretation, analysis and design. Designs should also be checked by an experienced geotechnical engineer. Lastly, proper supervision with the aid of checklists are essential for successful constructions.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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