WHY AIM FOR 90% CONSOLIDATION WITH GROUND TREATMENT FOR COASTAL RECLAMATION?

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ABSTRACT

In coastal reclamation over soft ground, platform settlement is often targeted to achieve 90% of subsoil consolidation at the end of the construction period. The consequences of the remaining 10% of settlement over time will cause continuing platform settlement, which will have significant effects on the serviceability of the platform especially differential settlement between platforms and piled structures. The serviceability problems of the platform may also cause breakages of utilities, which will have significant maintenance costs. In addition, the above-mentioned continuing settlement of the platform will also generate negative skin friction on piles driven into hard strata and reduces their factor of safety on bearing capacity. This paper examines and discusses the issues and proposes suggestions to overcome problems of reclamation with ground treatment using vertical drains and surcharge. This paper also examines the impact in terms of cost effectiveness, construction period etc. if the degree of consolidation at the end of construction is targeted at more than 90%.

Keywords: 100% degree of consolidation, vertical drains, surcharge, reclamation

1. Introduction

In coastal reclamation over soft ground, prefabricated vertical drains (PVD) with surcharge are commonly adopted as a ground improvement method to accelerate dissipation of excessive pore water pressure and thus achieve the required degree of consolidation in a shorter period. Generally, platform settlement is often targeted to achieve 90% of the subsoil consolidation at the end of the construction period. It is rarely aimed at 100% (based on magnitude of settlement) because this requires a longer time.

However, the remaining 10% of settlement over time will have consequential continuing platform settlement. Subsequently, this will have significant effects on the serviceability of the platform, especially differential settlement between platform and piled structures. In addition, the above-mentioned continuing settlement of the platform will also generate negative skin friction on piles driven into hard strata and reduces their factor of safety on bearing capacity.

This paper intends to examine and discuss the above-mentioned issues and propose suggestions to overcome problems of reclamation with ground treatment using vertical drains and surcharge. This paper also examines the impact in terms of cost

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effectiveness, construction period, etc. if the degree of consolidation for the proposed finished platform level at the end of construction is targeted to achieve more than 90%.

In order to analyse the effect of aiming for a higher degree of consolidation, a case study has been conducted for an area of 100 m x 100 m with 30 m thick compressible layer using typical Klang Clay (Tan et al. 2003 and Tan et al. 2004) properties. The subsoil parameters used in the case study are shown in Table 1 while undrained shear strength for typical Klang Clay (Tan et al. 2004) is presented in Figure 1. The existing ground levels are at about RL 3m and the finished platform levels are at RL 6m. In order to achieve the finished platform level, compensation fill is required as illustrated in Figure 2. In view of low undrained shear strength of the subsoil, the embankment is constructed in two stages where geotextile is used at the edge of the embankment as basal reinforcement to enhance the slope stability. Stage 1 is constructed with the rest period of 1 month to 1.5 months. Subsequently, construction of Stage 2 will be commenced and the rest period required for the final stage is discussed in this paper.

2. Current Practice and Common Problems in Coastal Reclamation

Generally, in coastal reclamation over soft ground, the degree of consolidation of the subsoil is aimed at 90% and the post construction settlement is normally limited as follows:

a) Total post construction settlement should be less than 400 mm
b) The post construction settlement for the first five (5) years should be less than 100 mm

Even though the post construction settlement and degree of consolidation are controlled within the specified tolerances, the remaining 10% of settlement will have consequential continuing platform settlement, and have significant effects on the serviceability of the platform especially differential settlement between platform and piled structures. The serviceability problems of the platform may also cause breakages of utilities, which will have significant long term maintenance costs.

Settlement analyses were carried out and the results revealed that the magnitude of the remaining 10% of settlement ranges from 2.3% to 5.2% of the fill height as shown in Figure 3. It only requires a few millimetres of relative displacement between the settling subsoil and the pile shaft surface to mobilize negative skin friction on piles driven into hard strata.

3. Issues in Aiming for Higher Degrees of Consolidation

In order to overcome the common problems such as costly maintenance and reduction of the factor of safety in pile bearing capacity, the degree of consolidation of the subsoil should be aimed at more than 90% (such as 100%) especially when ground treatment, such as vertical drains with surcharge is adopted in a reclamation project. However, when aiming for a higher degree of consolidation (more than 90%) at the end of a construction period, construction time and construction cost are the two major issues that need to be addressed.

Basically, vertical drains are adopted to accelerate dissipation of excess pore pressure in the subsoil due to the imposed fill, and thus achieve the required degree of consolidation within the allocated construction period. If the degree of consolidation is targeted at more than 90%, either a longer rest period or closer vertical drain spacing are required with additional measures. This will result in longer construction periods and higher construction costs. Therefore, the subsequent sections will examine the impact in terms of cost effectiveness and construction period if the degree of consolidation at the end of construction is targeted at more than 90%.

3.1 Issues of Construction Time

Generally, ground treatment methods using vertical drains can achieve 90% of degree of consolidation for subsoil (in term of magnitude of consolidation settlement) within rest period of few months as shown in Figure 4. Figure 4 shows the relationship between the rest period and the degree of consolidation with different PVD spacing (1.0 m to 1.5 m) without surcharge.

In addition, it is also observed that within three months rest period, the degree of consolidation for the subsoil can achieve 95%, which is more than the conventional design of 90% degree of consolidation. However, if the degree of consolidation for the subsoil is aimed at 100% in terms of magnitude of consolidation settlement, the rest period is about two times longer than the rest period for a 90% degree of consolidation, which ranges from 2 to 6 months, depending on the spacing of vertical drains. This implies that a longer construction period is required. Nonetheless, if the rest period is fixed at 3 months in terms of construction practicality, PVD with closer spacing ranging from 1.0 m to 1.1 m is required. This will end in higher construction costs.

Analysis has also been carried out to assess the effect of PVD with different surcharge heights on the rest period. Figure 5 shows the relationship between the rest period and degree of consolidation for PVD of 1.5 m spacing without surcharge and with different surcharge heights. The analysis reveals that within a three months rest period, the degree of consolidation for the subsoil can achieve 100% for all the proposed surcharge heights. This implies that with surcharge, the time for the subsoil to achieve 100% of the degree of consolidation can be expedited up to 2.0 to 3.7 times compare to PVD without surcharge.

In addition, if PVD with surcharge is designed, the subsoil only requires an additional half to one month rest period to achieve 100% degree of consolidation compared to the time required to achieve the conventional targeted 90% degree of consolidation. The difference in rest periods to achieve a 100% degree of consolidation compared to a 90% of degree of consolidation is given in Table 2. Nonetheless, the above-mentioned rest period is for final stage only excluding the additional construction time required for first stage.

Table 2 shows that the difference between the rest period (PVD with surcharge) to achieve 90% and 100% degree of consolidation is short compared to the total construction period. In fact, with the subsoil achieving 100% degree of consolidation, the post construction settlement can be eliminated and thus prevent costly maintenance

fees and mitigating the risk of negative skin friction (which will result in a low factor of safety for pile bearing capacity).

Although the analysis reveals that the rest period to achieve a 100% degree of consolidation can be shortened with an increment of surcharge height, it is not possible to construct the filled embankment (including surcharge) in single stage. This is because the subsoil generally consists of soft marine clay with low undrained shear strength. Therefore, the filled embankments in coastal reclamation works are commonly constructed in stages.

Nevertheless, if higher surcharge is required to accelerate the consolidation settlement in relatively short period and bearing capacity (embankment stability) is an issue, vacuum preloading become a better option. In vacuum preloading, the applied atmospheric pressure of 1 bar (100kN/m^2) will generate an equivalent fill height of at about 4.0 m with efficiency of 70% to 80%. As such, higher degree of consolidation can be achieved within relatively short period and eliminates the risk of embankment failures without multiple-stage loadings.

3.2 Issues of Construction Costs

As mentioned in the earlier section, if closer PVD spacing with surcharge are designed to achieve the 100% degree of consolidation, this will result in an increase of construction cost.

If the subsoil is targeted to achieve a 100% degree of consolidation within the allocated time frame, PVD with closer spacing and with extra surcharge is required. With closer spacing, the number of PVD locations per unit area will increase and result in higher costs for PVD. Figure 6 shows the relationship of PVD spacing to cost per unit area per unit length (RM/m^2/m) where the cost will increase 15% to 30% for every 0.1 m reduction of spacing. The cost of vertical drains alone will increase by 300% from 2.0 m spacing to 1.0 m.

Assessment of the effect of surcharge cost is based on the surcharge height shown in Figure 5. The relationship of cost per unit area with incremental of surcharge height is shown in Figure 7. The graph shows a linear relationship where the surcharge cost will increase RM15.00/m^2 for every increment of 1.0 m surcharge height.

4. Solution Options

In order to assess the impact on construction time and construction cost if the degree of consolidation is aimed at 100% instead of 90%, the following options are considered:

a) **Option 1** – PVD with 1.5 m spacing, degree of consolidation aimed at 90%
b) **Option 2** – PVD with 1.5 m spacing , degree of consolidation aimed at 100%
c) **Option 3** – PVD with 1.5 m spacing with 0.5 m surcharge height, degree of consolidation aimed at 90%
d) **Option 4** – PVD with 1.5 m spacing with 0.5 m surcharge height, degree of consolidation aimed at 100%

e) **Option 5** – PVD with 1.5 m spacing with 1.0 m surcharge height, degree of consolidation aimed at 90%
f) **Option 6** – PVD with 1.5 m spacing with 1.0 m surcharge height, degree of consolidation aimed at 100%
g) **Option 7** – PVD with 1.75 m spacing with 0.5 m surcharge height, degree of consolidation aimed at 100%
h) **Option 8** – PVD with 1.75 m spacing with 1.0 m surcharge height, degree of consolidation aimed at 100%

Cost analyses were carried out based on the following current market rates for the above-mentioned options:

a) PVD installed at square pattern – RM1.30/m
b) Surcharge – RM15.00/m^3

Figure 8 is plotted to show the relationship between cost per area and time of construction for the above-mentioned options of ground treatment with and without surcharge to achieve 90% and 100% degree of consolidation. The graph shows that Option 2 will require an almost three times longer construction period compared to Option 1 without any difference in cost. The cost of rest period has intentionally been left out as this item is very subjective.

However, the difference in rest period between Options 5 and 6 is only about two weeks, in which the subsoil only requires an additional two weeks to achieve 100% degree of consolidation compared to 90% degree of consolidation at the same cost. This implies no significant effects on construction time even though the degree of consolidation for the subsoil is aimed at 100% instead of 90%. As such, this will mitigate costly long term maintenance and reduce the risk of low safety factor on bearing capacity for pile foundations.

Options 7 and 8 use wider PVD spacing of 1.75 m with surcharge of 0.5 m and 1.0 m height respectively and the degree of consolidation is aimed at 100%. As shown in Figure 6, Option 7 offers a cheaper solution when using PVD with surcharge compared to other options where 3.5 months is required to achieve a 100% degree of consolidation. Thus, it is shown that aiming for a higher degree of consolidation may not necessarily result in very significant cost increases as long as the design is optimised.

Nonetheless, it is observed that the increase in cost per unit area for PVD with surcharge is due to the handling cost of surcharge. Therefore, if surcharge material is available at the site, PVD with surcharge seems to be the best option to overcome the earlier mentioned problems. In fact, the additional cost paid on the surcharge material in order to achieve higher degree of consolidation could be cheaper than the long term maintenance and other consequential costs that need to be borne due to remaining continuing settlement upon completion of works.

5.0 Conclusion

In reclamation works of soft ground area, it is commonly targeted to achieve a 90% degree of consolidation instead of a 100% degree of consolidation. This is because it is

believed that a 100% degree of consolidation will result in a longer construction period and higher construction costs.

However, if PVD with surcharge is adopted as a ground treatment method to accelerate the consolidation process of subsoil, the subsoil only requires an additional half to one month rest period to achieve a 100% degree of consolidation compared to the time required to achieve the conventional targeted 90% degree of consolidation. This shows that the difference between the rest period (PVD with surcharge) to achieve a 90% and 100% degree of consolidation is short compared to the total construction period. In fact, this can be done with the same construction costs.

Therefore, no additional cost is required and only a very insignificant additional rest period is needed if the degree of consolidation for the subsoil is aimed at 100% instead of the conventional 90% in coastal reclamation works. This will eliminate the remaining continuing settlement. Subsequently, this will mitigate costly long term maintenance and reduce the risk of a low safety factor on bearing capacity for pile foundation.

Unit Weight (kN/m^3)	13.5 – 15.5
Overconsolidation Ratio	1.2 – 8.0
Compression Ratio	0.265-0.357
Recompression Ratio	0.041-0.056
Coefficient of Consolidation in Vertical Direction (m^2/yr)	7-10
Coefficient of Consolidation in Horizontal Direction (m^2/yr)	14.0
Compressible Soft Layer Thickness (m)	30.0
Water Table (m below ground level)	0.5

Table 1. Subsoil Parameters

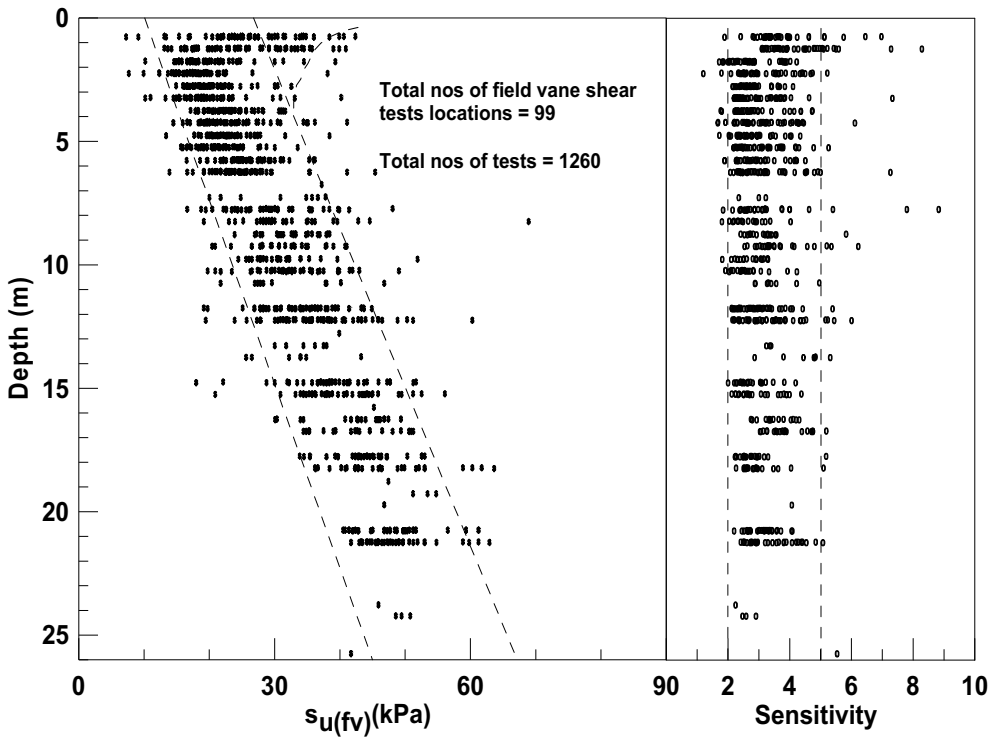

Figure 1. Undrained Shear Strength and Sensitivity of Klang Clay (Tan et. al. 2004)

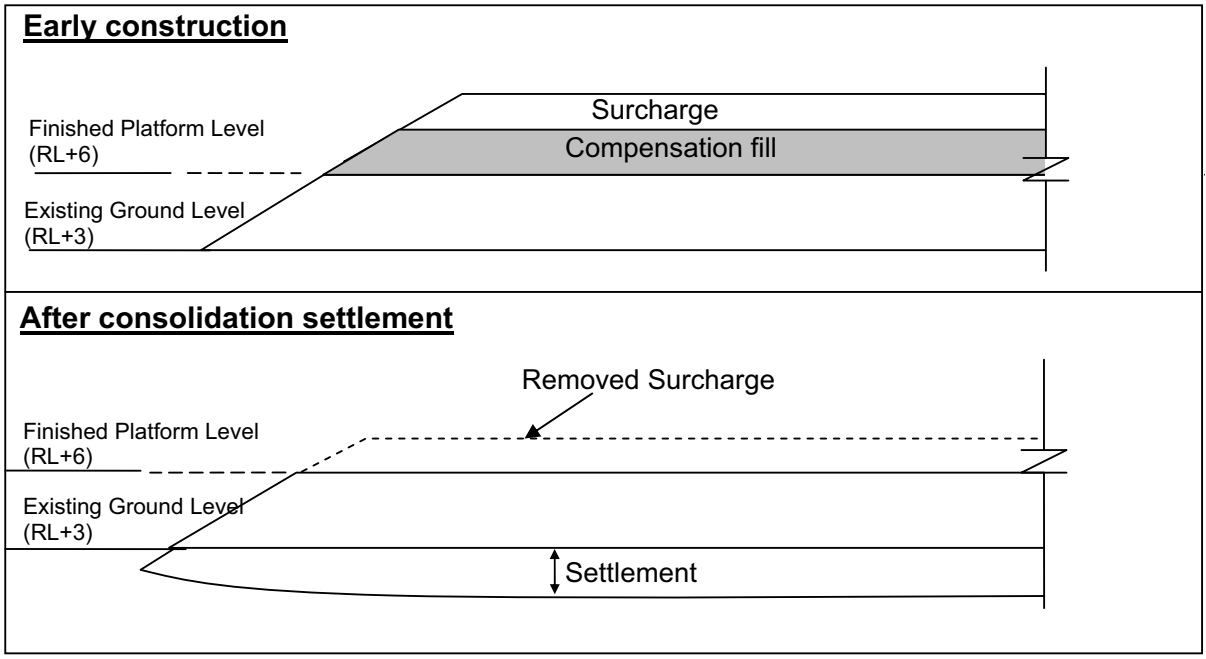

Figure 2. Concept of Surcharging

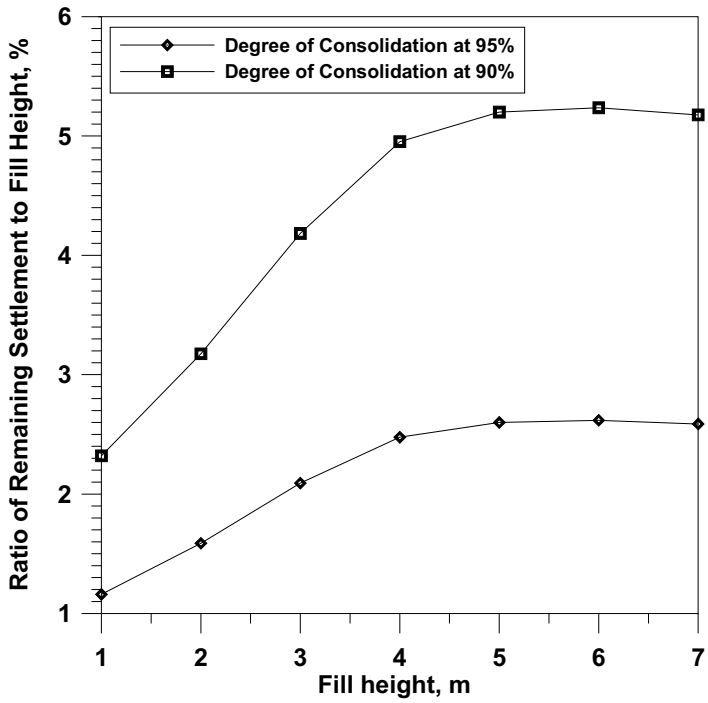

Figure 3. Relationship between Ratio of Remaining Settlement and Fill Height

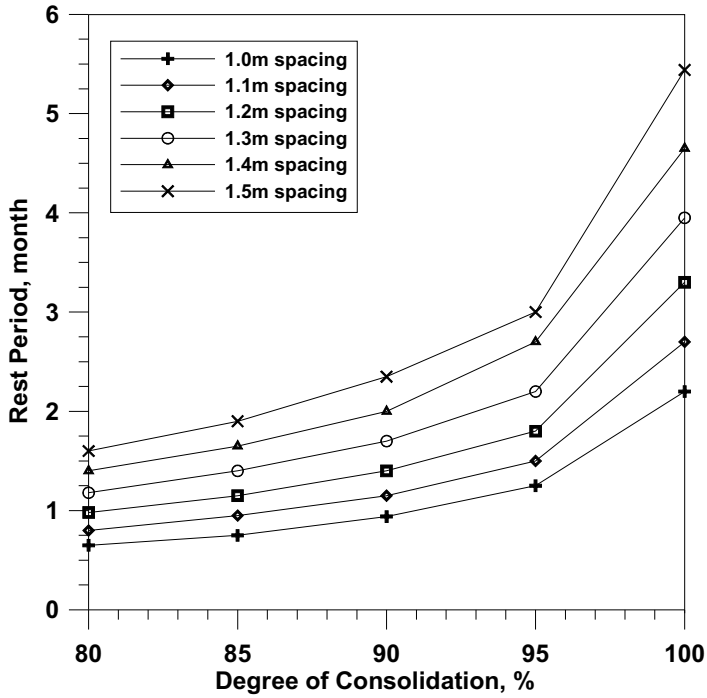

Figure 4. Relationship between Rest Period and Degree of Consolidation for Different PVD Spacing

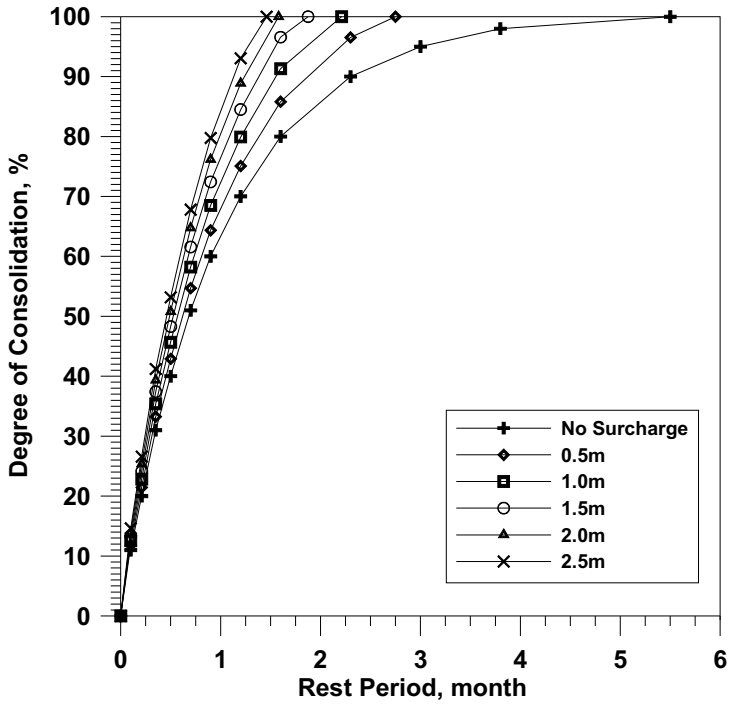

Figure 5. Relationship between Degree of Consolidation and Rest Period for PVD 1.5 m Spacing with Different Surcharge Heights

Surcharge Height (m)	Time Required (month)		Difference (month)
	90% Degree	100% Degree	
0.50	1.88	2.75	0.87
1.00	1.65	2.21	0.56
1.50	1.42	1.88	0.46
2.00	1.25	1.58	0.33
2.50	1.13	1.46	0.33

Table 2. Effects of Different Surcharge Heights on Time Required in Achieving 90% and 100% Degree of Consolidation Using PVD 1.5 m Spacing

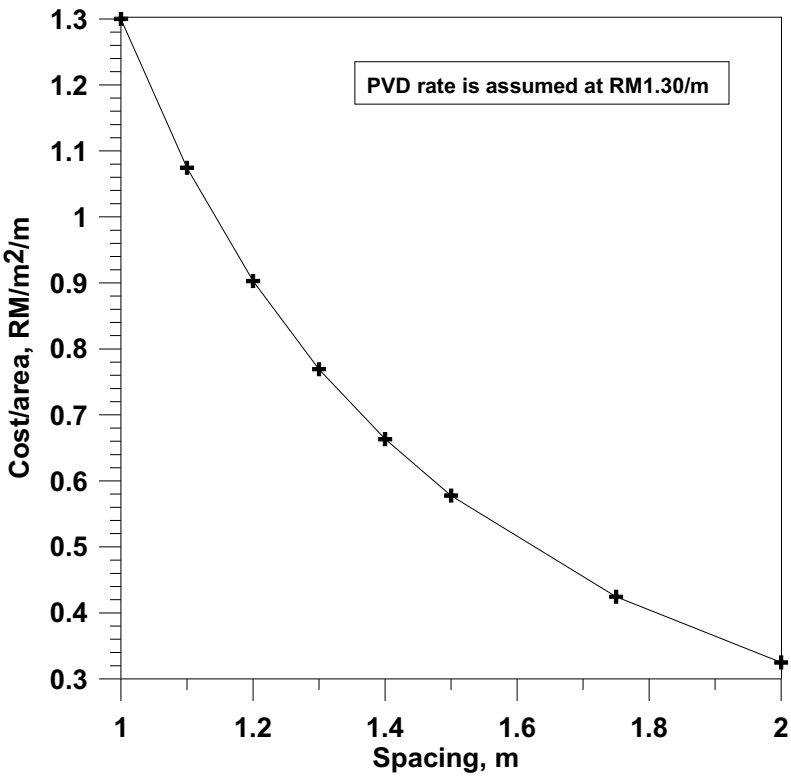

Figure 6. Relationship between Cost of PVD per Area per Length and PVD Spacing

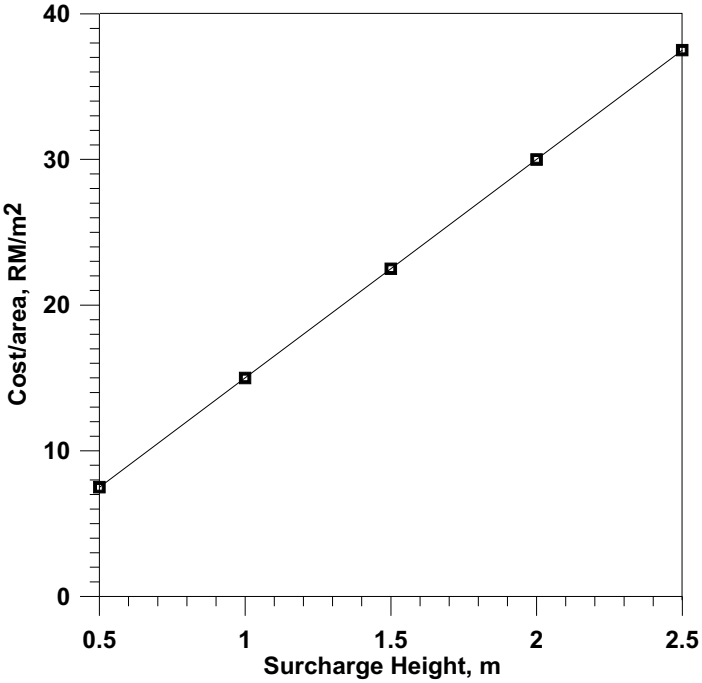

Figure 7. Relationship between Cost of Surcharge per Area and Surcharge Height

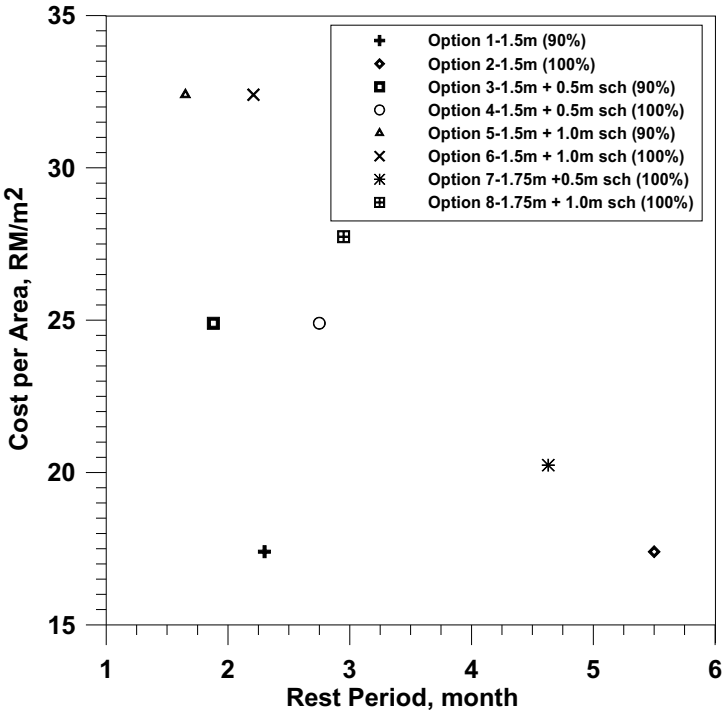

Figure 8. Relationship between Cost of Ground Treatment per Area and Rest Period

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