Modelling of reclamation of soft ground by geosynthetic layer beneath the granular fill

K. Ramu and M.R. Madhav
Department of Civil Engineering, Indian Institute of Technology, Kanpur, India

Keywords: Coastal works, Embankments, Numerical modelling, Reclamation, Reinforcement

ABSTRACT: The reclamation process is modeled as a new moving boundary problem for the prediction of deformations during reclamation, by extending the Madhav and Poorooshasb (1988) model. The non-linear responses of soft sub-grade soil and the granular fill are represented by Winkler springs and the Pasternak shear layer respectively while the geosynthetic layer is modeled as a rough membrane. Since the ground is very soft, very large settlements are expected during the placement of the granular fill. In the proposed model the shear stress at the interface of the granular fill and the reinforcement at any point is made equal to the vertical shear stress at that point but limited to the interface shear resistance, i.e. equal to the product of normal stress and the tangent of the interface coefficient of friction. The model developed is based on the finite or large deformation theory. A parametric study is carried out for the deformations and tension in the reinforcing layer obtained as a function of weight of the fill, shear stiffness of the granular fill, undrained strength of the subgrade soil and the width of the reclaimed area. The actual length of the reinforcement and the volume of the fill required are then estimated form the predicted deformation profiles.

1 INTRODUCTION

Most coastal lands consist of very soft marine deposits and often get inundated. To make these grounds suitable for development, they have to be reclaimed by placing suitable material over the soft ground to improve bearing capacity and to reduce settlements of the structures founded on them. In general, reclamation is carried out by spreading granular material over the soft ground and allowing it to settle uniformly into the soft ground under its self-weight. But if the ground is very soft, it is very difficult to spread the granular material as it sinks into the ground non-uniformly. To ease the spreading of the granular fill, a geosynthetic, often a geogrid is laid over the soft ground and the granular material spread over it. The goesynthetic reduces the overall settlements, distributes the loads uniformly and prevents non – uniform sinking of the granular material into the ground.

Imanishi et al. (1996) developed a two dimensional deformation system (DDS) that can monitor the shape of the sand displacement. Using this DDS, they monitor the shape of the sand replacement process and tension developed in the geonet during the reclamation process. Imanishi el al. (1998) presented an approach based on cable theory to estimate the deformation and stress distribution in the geogrid laid on soft clay ground. In their analysis they had considered only the final shape of the geogrid. They observed that the maximum tensile stress occurs at the end of dyke/embankment and that the magnitude of the tensile stress is less than the product of the initial width of geonet and the shear resistance between geonet and soft clay ground. The general construction procedure for reclamation, normally follows that shown in Figure.1 (Lawson 1999). In this paper, a model is proposed for the process of reclamation as given by Lawson (1999) on a super-soft ground (Fig.1) and analysed. Since the reclamation process involves very high settlements of the fill into the ground, infinitesimal theory may not give good results and hence a finite deformation theory is proposed with an incremental approach.

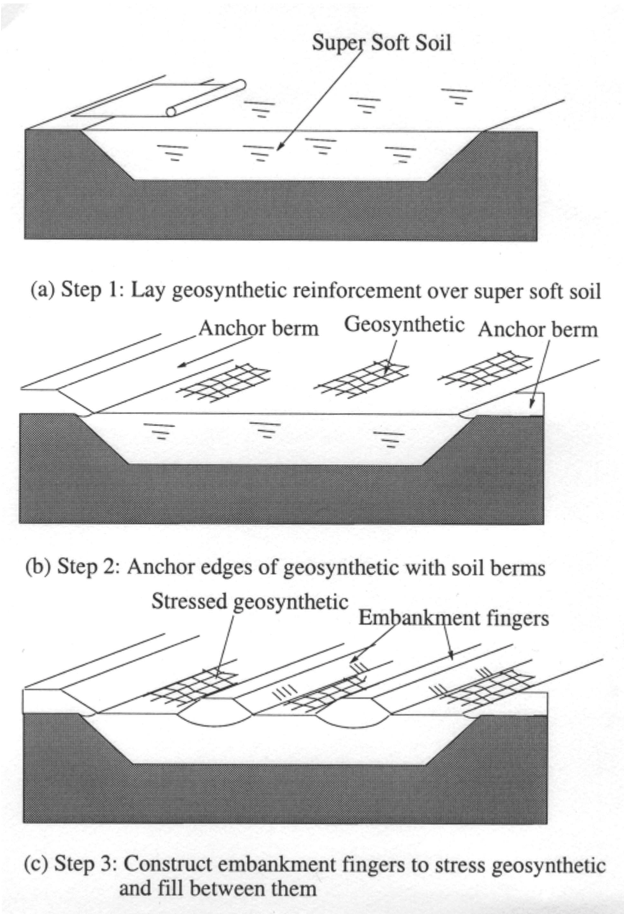

Figure 1. Construction sequence for the reclamation of super-soft soil deposits using geosynthetic reinforcement (After Lawson, 1999)

2 PROPOSED MODEL AND ANALYSIS

The process of reclamation consists of laying a sheet of geosynthetic, often a geogrid or a geotextile, construct an embankment/bund as shown in Figure. 1, spread the granular fill between the two embankments in stages (Fig. 2) and compact it. The ground settles under the self weight of the granular fill. However the fill placed during the previous lift acts as a shear layer. Hence the process of reclamation is modeled as a reinforced granular fill on soft ground but with both weight and shear stiffness increasing with each lift of granular fill. The increase in weight of each lift of the granular fill, $\Delta q = \gamma \Delta H$, where ΔH is the increase in settlement due to the self weight of the previous lift of granular fill and γ is the density of the granular fill. The increase in shear stiffness for the each lift, $\Delta G = G_s \Delta H$, where G_s is the shear modulus of the granular fill.

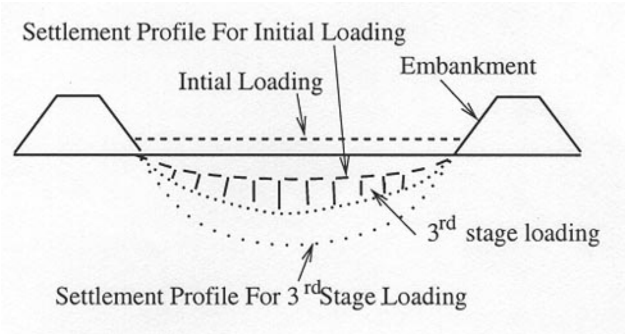

Figure 2. Process of Reclamation

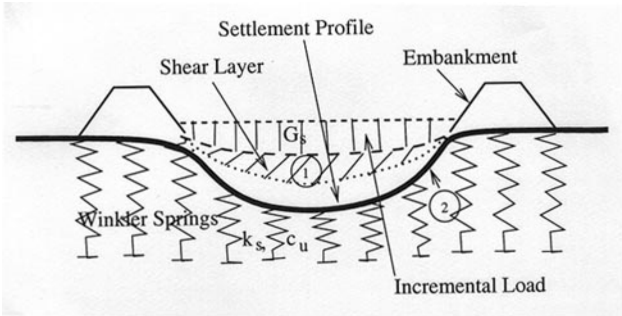

Figure 3. Proposed model for 3rd Stage of Reclamation

The reclamation process of ground on the soft soil (Fig. 1c) between the two embankments is modeled as shown in Figure. 3. In the model, the soft subgrade soil is represented by elasto – plastic springs, the granular fill by Pasternak shear layer and the geosynthetic layer by the rough membrane. In this analysis the width of the reinforcement layer is large enough to extend under the embankments. The initial height of the granular fill is taken as 0.2 m for first stage and the cavity formed to due to settlement from the previous fill is filled, compacted and allowed it to settle. A hyperbolic stress – displacement response for the soft soil with initial slope of k_s, ultimate bearing capacity equal to q_f and a hyperbolic shear stress- strain response of the granular fill with initial shear modulus equal to G_s, the maximum shear resistance equal to τ_f are assumed. Using finite deformation theory with incremental approach (Ramu et al. 1999) the increment in shear strain with the increment in load-intensity, Δq (=$\gamma\Delta H$), is derived as

$$Tan\Delta\theta \cong \Delta\theta = \frac{-\left(d\Delta w/dx\right)}{\left(1+\tan^2\theta - \tan\theta\,\dfrac{d\Delta w}{dx}\right)} \tag{1}$$

where x and w are the distance from the centerline of the reclaimed ground and the settlement at that distance respectively, Δw and $\Delta\theta$ are the incremental settlement and shear strain respectively. If the increments in the applied stress, Δq, are small, so would be the increments in the shear strains, $\Delta\theta$ and Eq. (1) is valid.

Consider two elements (1) and (2) shown in Fig. 3, chosen to represent the mechanics of the reclamation at any stage. With the incremental load of intensity, Δq, the governing equation for the granular fill (element 1, Fig. 4a), based on Pasternak shear layer concept, can be derived as

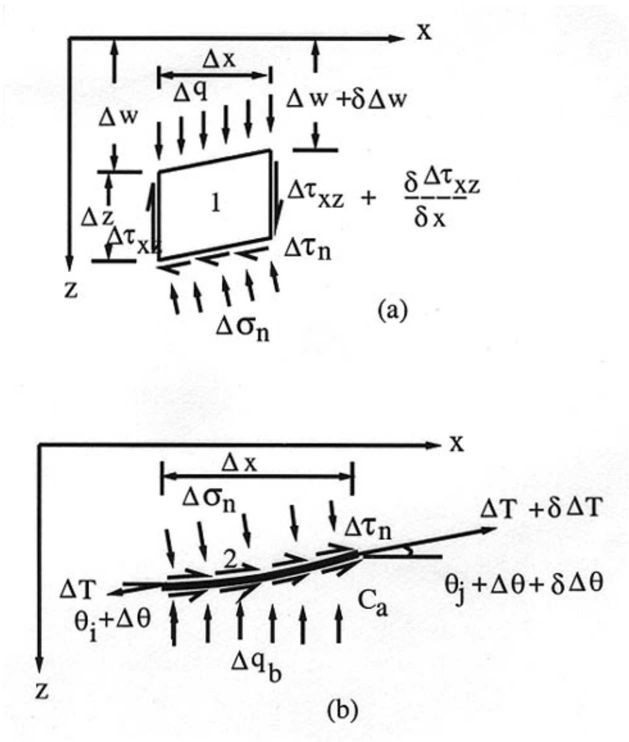

Figure 4. Forces (a) on the Granular fill and (b) on the Reinforcement Element

$$\Delta q = \Delta\sigma_n - \Delta\tau_n \tan(\theta_i + \Delta\theta) + \frac{\partial \Delta N_x}{\partial x} \tag{2}$$

where $\Delta\sigma_n$ and $\Delta\tau_n$ are the normal and shear stress at the bottom of the shear layer, θ_i and $\Delta\theta$ are the inclination of the deformed shape of the granular fill at the end of the previous lift and the incremental inclination of the deformed shape caused by the incremental load, Δq. The variation of shear force along the vertical face of the element 1 is

$$\frac{\partial \Delta N_x}{\partial x} = -GH\left[\frac{c_1 \dfrac{d^2\Delta w}{dx^2} + c_2 \dfrac{d\Delta w}{dx}\dfrac{d^2 w}{dx^2}}{(1+\beta_g\theta)^2 c_3^2}\right] \tag{3}$$

where $c_1 = 1 + \tan^2\theta$ $c_2 = \left\{\left(2\tan\theta - \dfrac{d\Delta w}{dx}\right) + \dfrac{2\beta_g}{(1+\beta_g\theta)} c_3 \cos^2\theta\right\}$ and

$c_3 = \left(1 + \tan^2\theta - \tan\theta \dfrac{d\Delta w}{dx}\right)$

Substituting Eq. (3) in Eq. (2) one gets,

$$\Delta q = \Delta\sigma_n - \Delta\tau_n \tan(\theta_i + \Delta\theta) - GH\left[\frac{c_1 \dfrac{d^2\Delta w}{dx^2} + c_2 \dfrac{d\Delta w}{dx}\dfrac{d^2 w}{dx^2}}{(1+\beta_g\theta)^2 c_3^2}\right] \qquad (4)$$

Considering the reinforcement element, (element 2, Fig 4b), the horizontal force equilibrium gives,

$$\frac{\partial\Delta T}{\partial x}\cos(\theta_i + \Delta\theta) - \Delta T \sin(\theta_i + \Delta\theta)\frac{d\delta\Delta\theta}{dx} = -\Delta\sigma_n \tan(\theta_i + \Delta\theta) - (\Delta\tau_n - \Delta c_a) \quad (5)$$

where ΔT is incremental tension developed by the incremental increase in intensity of load, Δq^*, and Δc_a is the incremental cohesion at the interface of the geonet and the soft subgrade soil. The vertical equilibrium of the forces in the reinforcement yields

$$\frac{\partial\Delta T}{\partial x}\sin(\theta_i + \Delta\theta) + \Delta T \cos(\theta_i + \Delta\theta)\frac{d\delta\Delta\theta}{dx} = \Delta\sigma_n - (\Delta\tau_n - \Delta c_a)\tan(\theta_i + \Delta\theta) - \Delta q_s \quad (6)$$

where Δq_s [= $k_s\,\Delta w/(1+\beta_s w)^2$] is the vertical incremental stress at the bottom of the reinforcement and β_s (= $k_s B/q_f$) is the non-linear response of the soft soil and k_s, B and q_f are the subgrade modulus of the soft soil, half the width of the reclamation and the ultimate bearing capacity of the soft soil respectively. Multiplying Eq. (5) by $\cos(\theta_i + \Delta\theta)$ and Eq. (5) with $\sin(\theta_i + \Delta\theta)$ and combining the two, one gets

$$\frac{\partial\Delta T}{\partial x} = -\frac{\Delta\tau_n + \Delta C_a}{\cos(\theta_i + \Delta\theta)} - \Delta q_s \sin(\theta_i + \Delta\theta) \qquad (7)$$

Eq. (7) gives the variation of incremental tension in the reinforcement with the incremetal intensity of load. Multiplying Eq. (5) by $\sin(\theta_i + \Delta\theta)$ and Eq. (6) $\cos(\theta_i + \Delta\theta)$ and combining the two, one gets

$$\Delta T \frac{d\delta\Delta\theta}{dx} = \frac{\Delta\sigma_n}{\cos(\theta_i + \Delta\theta)} - q_s \cos(\theta_i + \Delta\theta) \qquad (8)$$

Differentiating Eq. 1 with respective to x, one gets

$$\frac{\partial\delta\Delta\theta}{\partial x} = -\frac{c_i \dfrac{d^2\Delta w}{dx^2} + c_4}{c_3^2} \qquad (9)$$

where $c_4 = \dfrac{d\Delta w}{dx}\left\{2\tan\theta - \dfrac{d\Delta w}{dx}\right\}\dfrac{d^2 w}{dx^2}$

Substituting Eq. 9 in Eq. 8 one gets

$$-\Delta T \frac{c_1 \dfrac{d^2\Delta w}{dx^2} + c_4}{c_3^{\,2}} = \frac{\Delta\sigma_n}{\cos(\theta_i + \Delta\theta)} - q_s \cos(\theta + \Delta\theta) \qquad (10)$$

Combining Eq.s (10) and (7) with Eq. (3), one gets

$$\Delta q_z = -\Delta T \cos(\theta_i + \Delta\theta)\frac{\left(c_1 \dfrac{d^2\Delta w}{dx^2} + c_4\right)}{c_3^2} - GH\,\frac{\left(c_1 \dfrac{d^2\Delta w}{dx^2} + c_2 \dfrac{d\Delta w}{dx}\dfrac{d^2 w}{dx^2}\right)}{c_3^2}$$

$$+\frac{d\Delta T}{dx}\sin(\theta + \Delta\theta) - \Delta c \tan(\theta + \Delta\vartheta) + \Delta q_s \tag{11}$$

The shear stress at the vertical face of the element 1 is

$$\Delta\tau_n = \frac{G_s \Delta\theta}{\left(1 + \dfrac{G_s}{\tau_f}\theta\right)^2} \tag{12}$$

Substituting Eq. 12 in Eq 7 one gets

$$\frac{\partial\Delta T}{\partial x}\cos(\theta + \Delta\theta) = -\left[\frac{G_s \Delta\theta}{\left(1 + \dfrac{G_s}{\tau_f}\right)^2} + \Delta c_a\right] - \Delta q_s \sin(\theta_i + \Delta\theta)\cos(\theta_i + \Delta\theta) \tag{13}$$

Normalising with $q^* = q/k_cB$, $W=w/B$, $X=x/B$, $\Delta X=\Delta x/B$, $\Delta W=\Delta w/B$, $\Delta q^* = \Delta q/k_cB$, $C=\alpha c_u/k_sB$, $\Delta C=\alpha\Delta c_u/k_sB$ $\Delta T^*=\Delta T/k_sB^2$ and $G^*=GH/k_sB^2$. Eq.s. (11) and (13) become

$$\Delta q^* = -\Delta T \cos(\theta_i + \Delta\theta)\frac{\left(c_1^* \dfrac{d^2\Delta W}{dX^2} + c_4^*\right)}{\left(c_3^*\right)^2} - G^*\,\frac{\left(c_1^* \dfrac{d^2\Delta W}{dX^2} + c_2^* \dfrac{d\Delta W}{dX}\dfrac{d^2 W}{dX^2}\right)}{\left(c_3^*\right)^2}$$

$$+\frac{d\Delta T}{dX}\sin(\theta + \Delta\theta) - \Delta C \tan(\theta + \Delta\vartheta) + \Delta q_s^* \tag{14}$$

where

$$c_1^* = 1 + \tan^2\theta\,,\, c_2^* = \left\{\left(2\tan\theta - \frac{d\Delta W}{dX}\right) + \frac{2\beta_g}{(1+\beta_g\theta)}c_3^*\cos^2\theta\right\}$$

$$c_3^* = \left(1 + \tan^2\theta - \tan\theta\,\frac{d\Delta W}{dX}\right)\; c_4^* = \frac{d\Delta W}{dX}\left\{2\tan\theta - \frac{d\Delta W}{dX}\right\}\frac{d^2 W}{dX^2}$$

and

$$\frac{\partial\Delta T}{\partial X}\cos(\theta + \Delta\theta) = -\left[\frac{\left(G^*/H^*\right)\Delta\theta}{\left(1 + \dfrac{G_s}{\tau_f}\theta\right)^2} + \Delta C\right] - \Delta q_s^* \sin(\theta_i + \Delta\theta)\cos(\theta_i + \Delta\theta) \tag{15}$$

The boundary conditions are: at x = 0, $d\Delta w/dx = 0$ and at X = L, $d\Delta w/dx = 0$. Eq.s (14) and (15) are solved numerically to evaluate the settlement and tension in the reinforcement at any point by the finite difference method. Considering symmetry of the load and the reinforced zone, only half the width of the reinforced zone is considered for the analysis. Half the widths of the reclamation and the embankment portion are divided into 'n' and '(nt - n)' number of elements of length Δx. Eq.s (14) and (15) are solved iteratively for each increment in stress, Δq^*, with the boundary conditions to obtain the incremental settlements, ΔW and incremental tension in the reinforcement, ΔT^*. These incremental settlements are summed up to arrive at the total settlement as,

$$W_i^*(q+\Delta q) = W_i^*(q) + \Delta W_i^* \text{ for } 0 < i < nt+1 \qquad (16)$$

where W_i (q*) and W_i (q* + Δq*) are the normalised total settlements under loads of intensities, q* and q*+Δq* respectively. Similarly the total tension, T_i^*, in the reinforcement layer due to the incremental weight of the granular fill is

$$T_i^*(q+\Delta q) = T_i^*(q) + \Delta T_i^* \text{ for } 0 < i < nt+1 \qquad (17)$$

where T^*_i(q*) and T^*_i(q* + Δq*) are the normalised tensions under the loads of intensities, q* and q*+Δq* respectively. The extended length of the geosynthetic layer is calculated from the predicted deformation profile as

$$L_a = \sum_{i=1}^{nt} \sqrt{\left(dx^2 + \left(w_{i+1} - w_i\right)^2\right)} \qquad (18)$$

while the volume of the material, V, sunk into the ground is

$$V = \frac{dx}{3}\begin{bmatrix} w_1 + w_{nt+1} + 4\left(w_2 + w_4 + ...\right) \\ + 2\left(w_3 + w_5 + ...\right) \end{bmatrix} \qquad (19)$$

3 RESULTS AND DISCUSSION

The model proposed represents the process of reclamation of laying the geosynthetic, spreading and compacting the granular layer and the construction in stages. Eq.s 14 & 15 are solved iteratively to obtain the increments in settlements of the ground and tension in the geosynthetic for each stage of construction of the berm. These incremental settlements and tensions are summed up (Eq.s 16 & 17) to arrive at the total settlements and tensions at various points. Because of soft ground and large displacements, the geosynthetic gets dragged and the granular fill gets sunk into the ground. Hence, the extended length, L_a, of the geosynthetic and the volume, V, of the granular fill that sinks into the ground, are estimated (Eq.s 18 & 19) from settlement profile predicted.

As the process of reclamation on super-soft ground involves very large deformations, the problem has been cast as a moving boundary problem, updating the geometry at each stage of the construction.

To illustrate the efficacy of the method, results for one typical case are presented. The unit weight of fill is 16 kN/m^3. The embankment has top width 5 m and height 3 m with a side slopes of 2H:1V. The initial lift of the reclamation is restricted to 0.2 m. The shear modulus of the granular fill, G_s, is varied from 200 to 2000 kPa, the modulus of subgrade reaction, k_s, of the soft ground from 13.0 to 15.0 kN/m^3 and the undrained strength, c_u, from 5.0 to 20 kPa. The constant parameters taken in the parametric study are the width of reclamation, 'B' of 30 m, the modulus of subgrade reaction of the soil below the embankment of 200 kN/m^3.

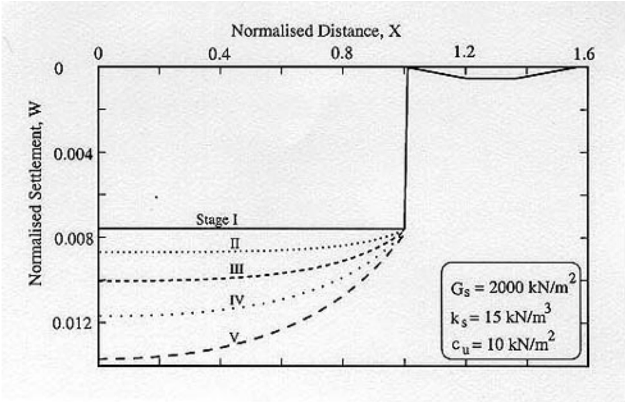

Figure 5. Variation of Settlement with the Distance during the Reclamation Process

Variations of normalised settlement of the ground and the normalised tension, T^*, with distance during the reclamation process are presented in Fig.s 5 & 6 respectively, for G_s = 2 MPa, k_s = 15 kN/m^3, c_u = 10 kPa. The settlement due to uniform fill of thickness 0.2 m placed over the total width of reclaimed area is about 0.007583. As the reclamation process is building up, the maximum settlement at the center increases to 0.013689 at the 5^{th} stage of the reclamation process. The variations in tensions with distance (Fig. 6) in contrast are uniform without any sharp kinks in the curves. For the initial reclamation of the area under 0.20 m thick fill, the maximum tension is 0.0030947 and tension increases to 0.014213 for the 5^{th} stage of the reclamation. The increase in tension in the reinforcement varies almost linearly with distance from to the edge to the center of the reclamation. For this case, the estimated length of the geosynthetic is only 1.5742 times 'B' in the first stage and 1.5745 B at the 5^{th} stage of reclamation, while the volume of the fill that sinks into the ground becomes 10.97 m^3 at the 5^{th} stage of reclamation.

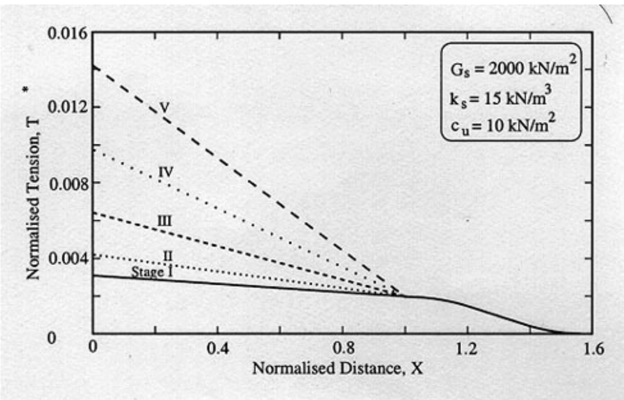

Figure 6. Variation of Tension with the Distance during the Reclamation Process

The influence of the shear modulus of fill material on settlement profile for 5^{th} stage of the reclamation is shown in Fig. 7 for k_s = 15 MN/m^3, c_u = 5 kPa. The normalised settlement at the center decreases from 0.03141 to 0.026588 for G_s increasing from 200.00 to 2000.0 kPa. With the increase in the shear stiffness of the fill, G^*, the load gets distributed to outside of the reclamation area. Hence the settlement in the reclamation area gets reduced. The variation of mobilised tension in the reinforcement is marginal (Fig. 8). The length of the reinforcement is 1.577 B and the volume of the fill that sinks into the ground becomes 26.33 m^3 at the 5th stage of the loading for G_s =200 kPa.

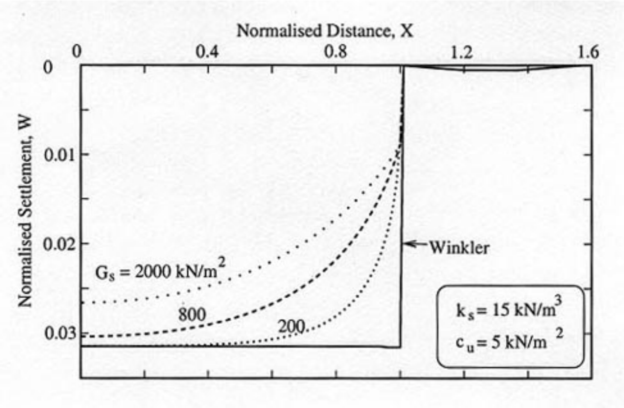

Figure 7. Variation of Settlement with Distance: Effect of G_s

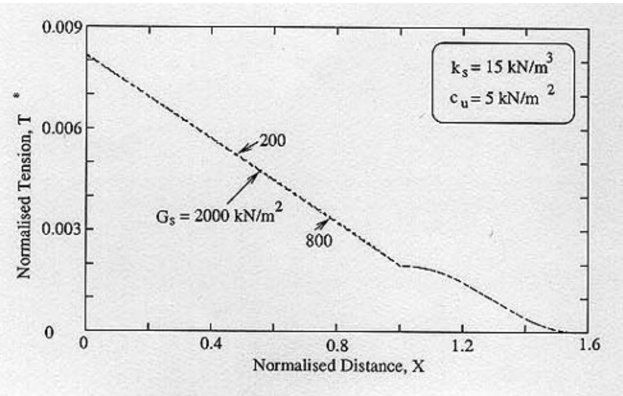

Figure 8. Variation of Tension with Distance: Effect of G_s

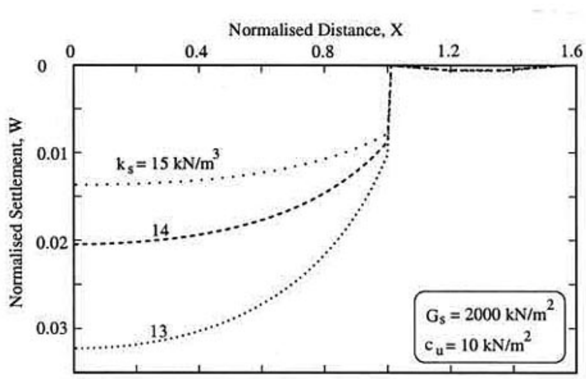

Figure 9. Variation of Settlement with Distance: Effect of k_s

Compared to the effect of G_s, the effect of the modulus of subgrade reaction of the soil, k_s, on settlement profiles appears (Fig. 9) to be significant. For a small increase (13.0 to 15.0 kN/m^3) of k_s, the maximum settlement reduces by about 17 %. i.e. from 0.0165 to 0.0137 for G_s = 2 MPa, c_u= 10 kPa. The shapes of the settlement profile curves become sharp with decreasing k_s. The effect of increase of k_s on the extended length of reinforcement is negligible while the volume of the material that sinks below ground level decreases by about 54.4 % (from 24.074 to 10.97 m^3). The mobilised tension in the reinforcement (Fig. 10) is decreases from 0.0322575 to 0.0142130

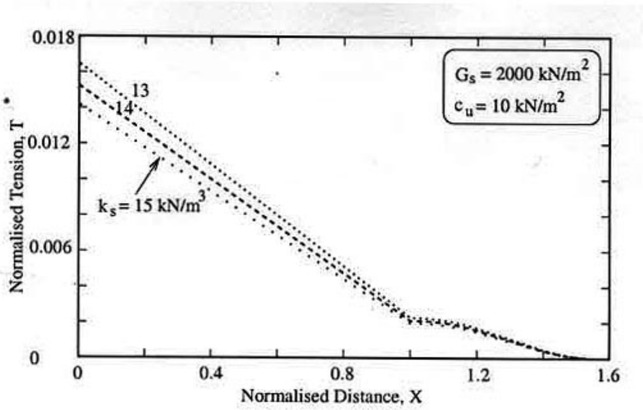

Figure 10. Variation of Tension with Distance: Effect of k_s

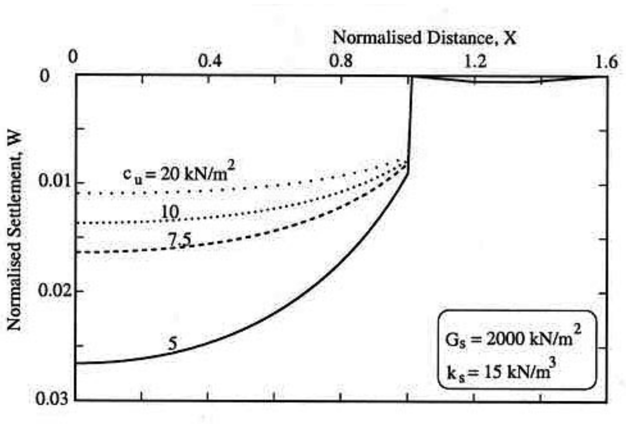

Figure 11. Variation of Settlement with Distance: Effect of c_u

In contrast, the effect of undrained strength of the soft soil on the settlement profiles is very significant (Fig. 11). For c_u increasing from 5.0 m to 20.0 kPa, a four-fold increase, maximum settlement decreases from 0.02658 to 0.01095, a decrease of 58.8%. As expected with the increase in undrained strength the settlement decreases, since the bearing capacity of the soft soil increases. Correspondingly the volume of material that sinks into the ground also reduces from 19.597 to 9.09 m^3 for c_u increasing from 5.0 to 20.0 kPa for the 5th stage of the loading. The mobilised tension in the reinforcement is presented in Fig. 12. The normalised tension in the reinforcement increases from 0.00813 to 0.02644 for c_u increasing from 5 to 20 kPa. This may be because of the increase in undrained cohesion causing more adhesion between the geosynthetic and the soft subgrade soil.

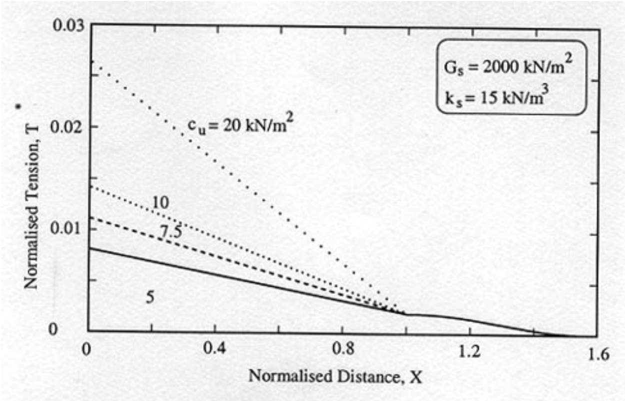

Figure 12. Variation of Tension with Distance: Effect of c_u

4 CONCLUSIONS

A new model is developed for the reclamation process (i) to predict the settlement of the granular fill into the ground, (ii) the tension developed in the reinforcement, (iii) the actual length of the geosynthetic and (iv) the quantity of fill that sinks into the ground. Since the reclamation process involves large deformations, the problem has been formulated and solved as a moving boundary problem. Using the finite deformation theory, the coordinates are updated for each step of reclamation. The effects of the parameters, viz. the shear stiffness of the granular material, G_s, the modulus of subgrade reaction, k_s, and the undrained strength, c_u, of the soft soil, on the settlement profile, tension, extended length of the reinforcement and the volume of material that sinks into the ground, are quantified.

REFERENCES

Imanishi H., Haratake N., Ochiai, H. & Asakuma M 1996. Behaviour of Sand Replacement with Geo-net on Reclaimed Marine Clay. Earth Reinforcement, Ochica Yasufuku *&* Omine*(*eds*),* Balkema, 1996, Rotterdam. *p* 597- 602.

Imanishi H., Ochiai H., Omine K. & Yamauchi M. 1998. Mechanical Behaviour of Geonet in Ground Replacement Method. Proceedings of the International Symposium on Lowland Technology, Saga University, Nov. 1998, Japan. p 301 – 308.

Lawson C.R. 1999. Earth Reinforcement Technique with Geosynthetics in Asean Region. Proceedings of the 11 th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Seoul, Korea, August, 1999. p 25 - 36 .

Madhav M. R. & Poorooshasb H. B. 1988. A New Model for Geosynthetic Reinforced Soil. Computers and Geotechnics, Vol6, No.4, p. 277 – 290.

Ramu K, Madhav M.R. & Poorooshasb H. B. 1999 Finite Strain Theory for Response of Granular Bed Overlying Soft Ground. Fourth Asia – Pacific Conference on Computational Mechanics, Singapore.