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Behaviour of Gravel Compaction Piles in Soft Clay

T.K.S. Fernando and N.H. Priyankara

Abstract: Gravel Compaction Pile (GCP) is one of the most widely used ground improvement techniques in the field of civil engineering for enhancing soft ground characteristics. However, notable knowledge gaps remain in understanding the behaviour of GCP-improved ground. Therefore, a numerical analysis was conducted using Plaxis-2D software to study the behaviour of GCP improved ground. Two models were developed using plane strain and axi-symmetric conditions and both models were validated using the data collected from the actual projects and existing literature. A parametric analysis was then performed using both models. The effect of permeability of GCP material was studied by considering the permeability ratio between GCP and surrounding soft soil. Based on the analysis, it was identified that when the permeability ratio exceeds 100, the stability of the GCP improved ground increases. The effect of the stiffness of the surrounding soil was also examined for different permeability ratios by considering different volumetric compressibility ratios. Additionally, this paper discusses the impact of encasement on composite ground by considering different encasement stiffnesses. Finally, the critical length of the GCP was determined as 11-12 m for ground improvement in very soft soil.

Keywords: Critical Length, Encasement Stiffness, Gravel Compaction Pile, Numerical Modelling, Parametric Study

1. Introduction

Countries with fast growing population or those in rapid development require a significant quantity of new structures and infrastructure. It is necessary to construct new infrastructure facilities on existing land where the subsoil conditions may not be very sound because the majority of areas with good subsoil conditions have been already used. In Sri Lanka, for instance, a significant portion of expressway development projects, including the Southern, Outer Circular, and Colombo-Katunayake, were built on the extremely weak subsurface conditions [1-6].

The inherent characteristics of soft soil, such as high moisture content, high compressibility, high void ratio, and very low shear strength, make constructing road embankments over them extremely difficult. These characteristics can lead to excessive settlement and instability of embankment slopes both during the road construction and operation [2-4][6-7]. As such, ground improvement techniques are frequently employed to enhance the engineering properties of subsurface soils that are poor and unable to support the structural load. Among these techniques, Gravel Compaction Pile (GCP) is one of the most widely used ground improvement methods adopted in the infrastructure development projects [1][7-8].

GCP is a type of pile constructed by digging a hole in the ground and filling it with gravel in layers and compacting each layer sequentially [1][7-8]. It can be used as load-bearing subsurface structure or as vertical drain that accelerate the consolidation process in soft soils [9]. The performance of GCP is highly dependent on the lateral confinement provided by the surrounding soil [8]. However, if the lateral confinement provided by soft soil is not sufficient, granular columns may lead to bulging and eventual failure [8][10]. Many researchers have reported that this issue can be resolved by encasing the column material to increase its lateral confinement. Further, it was noted that lateral confinement is proportional to the stiffness of the encasement [10-17].

Despite modifications made to Gravel Compaction Piles (GCPs) for their effective utilization, their behaviour remains questionable, and grounds improved by GCPs still experience failures [8]. This technique has been successfully applied during the construction of the Colombo-Katunayake Expressway project and the Outer Circular

Eng. T.K.S. Fernando, AMIE(SL), B.Sc. Eng. (Hons) (Ruhuna), PhD Student, Queensland University of Technology, Australia
Email:kaveeshasandeshfdo@gmail.com
ORCID ID: https://orcid.org/0009-0004-6779-5562

Eng. (Prof.) N.H. Priyankara, MIE(SL), PhD (Tohoku), MEng (AIT), B.Sc. Eng. (Hons) (Moratuwa), CEng, MSLGS, MISSMGE, Department of Civil and Environmental Engineering, University of Ruhuna, Sri Lanka.
Email:nadeej@cee.ruh.ac.lk
ORCID ID: http://orcid.org/0000-0002-8775-7246

Highway (OCH) project in Sri Lanka. However, the GCP technique failed in the Southern Expressway Extension Project from the Matara to Beliatta (section-1) in Sri Lanka [8]. This implies that still there is a lack of comprehensive knowledge on the behaviour of GCP improved grounds.

To understand the behaviour of GCP improved grounds, parametric studies have been conducted in various ways throughout history [10-17]. Parametric analysis involves studying the behaviour of a model by changing only one parameter at a time. Hence, the effect of that particular parameter on the behaviour of the entire model can be easily identified. Most researchers have conducted parametric analysis through numerical modelling, using software packages such as Plaxis, GeoFem, and Abaqus [10-17].

However, Almeida et al. [18] performed an analysis based on the data collected from a trial embankment supported on GCPs. They studied the effect of encasement on GCPs by examining settlement, lateral displacement, vertical stresses, excess porewater pressure over time, and GCP length for both encased and ordinary GCPs using field instrumentation. Due to the limitations of instruments and other facilities, it is challenging to always perform parametric analyses by developing physical models. As such, numerical modelling is an effective way to conduct parametric study on GCP improved ground.

2. Literature Review of Parametric Analysis on GCP

In numerical modelling of GCP improved ground, some studies were conducted using 2D models [10-12][15][19], some used 3D models [5], and others utilized both types [14][16-17]. The 2D models can be further divided into two categories, namely plane strain and axi-symmetric. The plane strain model is used for geometries with uniform cross-sections and stress state and loading scheme perpendicular to the z-direction (vertical direction). The axi-symmetric model is used for circular structures with uniform radial cross-sections, where loading is centered on the central axis [20].

Building upon this classification, numerical studies in the literature have developed single [10–15] or multiple [16–17] GCP models in 2D or 3D and conducted parametric analyses to examine behaviour changes by varying one material or model parameter at a time.

Among these parametric analysis studies, many numerical modelling investigations on GCPs focused on the effect of vertical encasement of granular piles. Lateral displacement variation along the depth of GCPs was studied for both vertically encased GCPs and ordinary GCPs. Results showed significantly reduced lateral displacement in encased GCPs compared to ordinary columns [10–17]. In addition, several other parametric studies were performed to study the influence of stiffness of the encasement [11][15], the effect of hoop tension force in the encasement [15][17], and the influence of the depth of encasement in GCPs [11][14-15]. They primarily focused on how the stability of GCP improves with varying stiffness of encasement material and critical length of the encasement for the better performance of GCPs. Thakur et al. [16] on the other hand discussed both horizontal and vertical encasements and analysed the load settlement curves.

In addition to encasement characteristics, two of the most important parameters of a granular column that affect the performance are its diameter and length. Alkhorshid et al. [10] and Murugesan and Rajagopal [15] studied the effect of GCP diameter on stress concentration ratio (n) and settlement of GCP improved ground. Marina et al. [14] performed a systematic analysis to determine the critical length of encased GCPs. They analysed the GCP length until no further settlement reduction occurs, considering various factors such as area replacement ratio (a_s), stiffness of encasement material, soft soil shear strength, friction angle of GCP material, applied load, soft soil layer thickness, and stiffness of GCP material. They found that the critical length would be about 1.1 to 1.9 times the GCP diameter for ordinary granular columns and about 1.3 to 2.5 times the GCP diameter for encased granular columns.

Further parametric investigations extended to other influencing factors such as material properties and site conditions. Numerous researchers used parametric analysis to investigate how the friction angle of granular column material affected the effectiveness of GCP improved ground [10-11]. Additionally, Debbabi et al. [11] studied the influence of soft soil layer thickness on the performance of GCPs, while Murugesan and Rajagopal [15] studied the influence of shear strength of surrounding soft soil on the load transfer to the founding soil. Since GCPs are used to support the embankments, Debbabi et al. [11] and Yoo and

Kim [17] studied the effect of different embankment heights on the behaviour of GCPs. Using an analytical approach, Alkhorshid et al. [10] studied the effect of stiffness of geosynthetic encasement on the stress concentration ratio of GCP improved ground. They compared the results obtained from analytical study with the finite element analysis. On the other hand, Kaliakin et al. [13] carried out different finite element analyses with various material constitutive models such as hardening, Mohr-Coulomb, etc. and presented the GCP behaviour accordingly.

Based on the literature review, it can be noted that only limited studies have been conducted to understand the effect of drainage ability of GCP material, lateral deformation behaviour of granular columns due to vertical load and effective length of GCP to carry the vertical load without failure. Therefore, in this research study, parametric analyses were carried out to gain comprehensive insight into the behaviour of GCP-improved ground using Plaxis 2D software.

3. Finite Element Modelling

Since finite element modelling has been identified as an effective way to study the behaviour of GCP improved ground, two models have been used in this research study. One model represents an actual GCP improved ground in the Outer Circular Expressway (OCH) – Northern Section 1 in Sri Lanka, and it was successfully simulated by Fernando et al. [19] using Plaxis 2D. The other model is a unit cell developed by Alkhorshid et al. [10] using Plaxis 2D.

3.1. Development of Finite Element Models

3.1.1. OCH - Northern Section 1 Model

Based on the data collected from Brinkgreve [20], Brinkgreve [21], Karunawardana et al. [1] and Tan et al. [18], a geometric model was developed to study the GCP behaviour using Plaxis 2D software. The typical cross section of the GCP improved embankment used for the analysis is shown in Figure 1.

The sub surface mainly consists of 1.5 m thick, soft silty clay layer followed by 4.0 m thick very soft peaty clay layer. Loose silty sand and medium dense sand layers are below the very soft peaty clay layer. The water table was at the existing ground surface. The average embankment height is 12.0 m, and it was constructed on a 0.5 m thick working platform. A gravel mat together with a geotextile has been placed as a drainage layer prior to the embankment filling. A geogrid has been laid at the bottom of the embankment to enhance the slope stability.

According to field records, the GCPs were installed down to a depth of about 9.0 m. The diameter of GCP is 0.7 m and GCPs were installed in a square grid pattern with a spacing of 1.2 m. Hence the area replacement ratio can be estimated as 0.27. Due to symmetricity, only right half of the embankment was considered for the analysis.

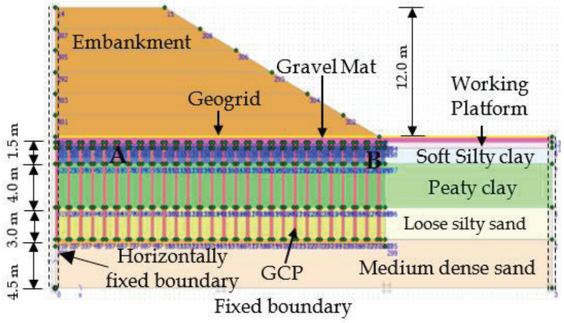

Figure 1- Generalized model geometry of OCH- Northern section 1

In the analysis, bottom boundary was kept fixed since completely weathered rock was encountered underneath and it was closed for the water flow. Left and right boundaries were restrained in the horizontal direction only, but free in the vertical direction. The free flow was not allowed at both left and right boundaries. Left boundary represents the line of the symmetry while right boundary depicts the end of the unimproved area.

Material parameters and constitutive models adopted in the analyses are shown in Table 1. The material properties were obtained from Karunawardana et al. [1] and related literature. For this analysis, Soft Soil (SS) constitutive model was used to model the soft peaty clay whereas Mohr-Coulomb (MC) constitutive model was used for the Gravel mat, GCP fill material and embankment. Medium mesh size was adopted for the model.

The construction stages of the model consist of GCP installation, followed by a 30-day consolidation period, after which a gravel mat was placed. The embankment was then constructed in six stages, each with a fill height of 2 m. After each filling stage, a consolidation period was allowed. Finally, a preloading period of 55 days was applied.

3.1.2. Unit Cell Model

Based on the procedure presented by Alkhorshid et al. [10] a unit cell model was developed to study the GCP behaviour as depicted in Figure 2. A GCP with a diameter of 0.8 m and a length of 10.0 m was used in a soft soil layer under a 10.0 m high embankment as the unit cell model.

Material parameters and constitutive models adopted in the analyses are shown in Table 2. The material properties were obtained from Alkhorshid et al. [10]. The Hardening (HD) constitutive model was used to model the soft soil layer whereas Mohr-Coulomb (MC) constitutive model was used for the rest of the materials in Plaxis 2D software. Medium mesh size was used in the numerical model.

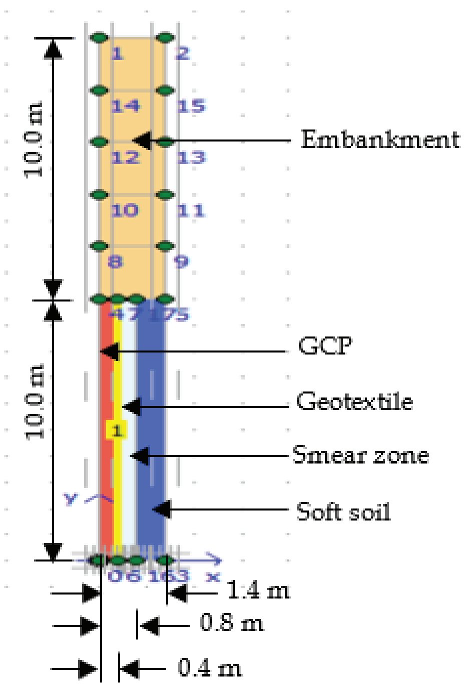

Figure 2 – Generalized model geometry of unit cell

3.2. Validation of the Models

Validation of developed models plays a crucial role in numerical modelling. Although it is difficult to model the exact behaviour, achieving the behaviour that closely approximates the real condition is essential for accurate analysis. Several methods have been identified for validation procedures. Murugesan and Rajagopal [15] used a previously developed model from the literature to validate their model. Yoo and Kim [17] used a case study of a real situation for validation. Alkhorshid et al. [10] and Debbabi et al. [11] employed different analytical methods to validate their models. A completely different approach was adopted by Thakur et al. [16], who developed a physical model to validate their numerical model. The methods used for validation of numerical models used in this study are described in the following section.

3.2.1. OCH - Northern Section 1 Model

This model was validated based on the actual field data of the Outer Circular Highway Northern Section 1 Project presented by Karunawardana et al. [1]. Settlement versus time relationship and porewater pressure variation over time relationship were used for the validation purposes. The full validation procedure and results were presented in Fernando et al. [19].

3.2.2. Unit Cell Model

Developed unit cell model was validated using the data presented by Alkhorshid et al. [10]. The validation procedure focused on the settlement at the top of the GCP versus embankment height, and the results are depicted in Table 3. Since these values are almost equal, it can be concluded that the developed unit cell has been successfully validated.

4. Parametric Analysis

After successfully validating the two numerical models, parametric analyses were performed to study the GCP behaviour. Three main parametric studies were conducted, namely, the effect of drainage, the effect of surrounding confining pressure, and the effect of granular pile length on the stability of GCP improved ground. A summary of the varied parameters in this study is presented in Table 4.

4.1. Effect of Drainage on Stability of GCP Improved Ground

It is well known that coefficient of permeability of soft clay in horizontal direction is much higher than that of vertical direction [22-23]. When the soft ground is improved with GCP, pore water within the soft clay flow horizontally towards the GCP due to its higher horizontal permeability. Then, the collected pore water flows vertically upward towards the surface through the GCP using capillary action, enhancing the rate of consolidation as GCPs act as vertical drains. This implies that soft ground improvement due to GCP installation mainly depends on the drainage characteristics of GCP material. In Sri Lanka, the most common filling material used in GCPs is Aggregate Base Course

Table 1 – Material parameters for OCH – Northern Section 1 model

Parameter	Embankment	GCP	Gravel Mat	Soft Silty Clay	Very soft Peaty Clay	Loose Silty Sand	Medium Dense Sand
Constitutive model	MC	MC	MC	MC	SS	MC	MC
Drainage condition	Drained	Drained	Drained	Undrained	Undrained	Drained	Drained
Unit weight, γ (kN/m^3)	18	22	16	17	11	16.5	17
Horizontal Permeability, k_h (m/day)	0.1	1.92	1	0.03	0.0003	1	0.5
Vertical Permeability, k_v (m/day)	0.1	1.92	1	0.01	0.0001	1	0.5
Youngs modulus, E (kN/m^2)	25,000	40,000	50,000	25,000	-	20,000	30,000
Poisson ratio, υ	0.3	0.3	0.3	0.3	-	0.3	0.3
Cohesion, c'(kN/m^2)	5	1	1	3	1	1	1
Friction angle, φ'(°)	32	36	36	20	16	23	30
Dilatancy angle, Ψ(°)	0	0	0	0	0	0	0
Modified compression index, C_c'	-	-	-	-	0.28	-	-
Modified swelling index, C_s'	-	-	-	-	0.028	-	-

Table 2 – Material parameters for unit cell model

Parameter	Embankment	GCP	Soft Clay
Constitutive model	MC	MC	HD
Drainage condition	Drained	Drained	Undrained
Saturated unit weight, γ_{sat} (kN/m^3)	22	19	16
Youngs modulus, E (kN/m^2)	42,000	45,000	-
Friction angle, φ'(°)	35	39	23
Dilatancy angle, Ψ(°)	0	5	0
Cohesion, c'(kN/m^2)	6	0	7
Poisson ratio, υ	0.33	0.3	0.2
Secant stiffness in standard drained triaxial test, E_{50}^{ref} (kN/m^2)	-	-	2313
Tangent stiffness for primary oedometer loading, E_{oed}^{ref} (kN/m^2)	-	-	1850
Unloading/reloading stiffness, E_{ur}^{ref} (kN/m^2)	-	-	6938
K_0 value for normal consolidation	0.43	0.37	0.6
Power for stress-level dependency of stiffness, m	-	-	1
Reference stress for stiffnesses, p_{ref} (kN/m^2)	-	-	100
Over consolidation ratio, OCR	-	-	1

Table 3 – Validation of unit cell

Embankment height (m)	Settlement according to Alkhorshid et al., 2018 [10] (m)	Settlement according to developed unit cell model (m)
2	0.200	0.200
6	0.515	0.514
8	0.637	0.637
10	0.747	0.742

Table 4 – Parametric study

Study	Parameter	Values
Effect of drainage	Permeability Ratio	10, 100, 250, 500, 1000, 10000
	Volumetric compressibility ratio	10, 15, 25
Effect of surrounding confining pressure	Stiffness of geotextile (kN/m)	None, 1000, 5000, 10000
Effect of different GCP length	Length of GCP (m)	6, 9, 11, 13, 15, 17, 19, 21

(ABC), which is a mixture of various sizes of aggregates and quarry dust. Due to its well-graded nature, ABC may act as a low-permeability filling material within the GCP, potentially raising concerns regarding its drainage performance. Accordingly, permeability and volumetric compressibility of the GCP material and column clogging have been identified as the factors that affect the drainage capacity of a GCP [24]. The effect of drainage on the stability of GCP improved ground has been studied by analysing these factors using the developed OCH-Northern section 1 model. Since the column clogging effect cannot be precisely modelled using Plaxis 2D, it was not addressed in this research study.

4.1.1. Permeability of the GCP Material

The effect of permeability of the GCP material was identified by analysing the variation of pore water pressure over time for different permeability ratios as shown in Figure 3. The permeability ratio is defined as the permeability of the GCP material divided by the permeability of the surrounding soft soil. To study the effect of drainage, the permeability ratio was varied from 10 to 10,000 while keeping other factors remain constant.

It can be seen that, irrespective of the permeability ratio, maximum excess pore water pressure is generated at the end of embankment construction. Furthermore, with the increase in the permeability ratio, the development of excess pore water pressure decreases. At lower permeability ratios, high pore pressure development can be observed due to the low rate of consolidation. If the permeability ratio is more than 100, the maximum excess pore water pressure can be reduced by more than 60%. This clearly indicates that, to get the maximum benefit of the GCP improved ground, permeability of the GCP material should be greater than two orders of time that of surrounding soft clay.

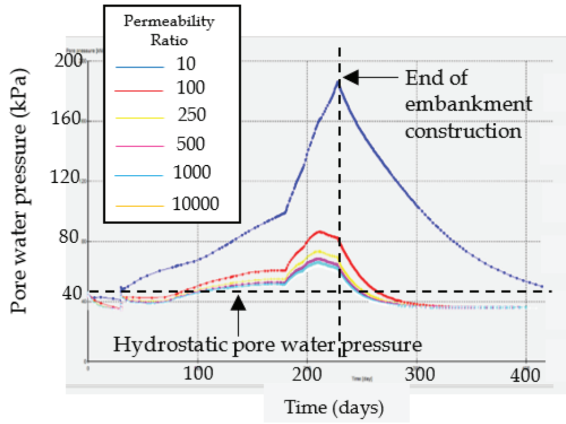

Figure 3 - Variation of porewater pressure versus time for different permeability ratios

4.1.2. Volumetric Compressibility of the GCP Material

To identify the effect of volumetric compressibility of GCP material, three permeability ratios namely 10, 100 and 1000 were selected from the above analysis. The volumetric compressibility of an elastic body (m_v) can be expressed as shown in Equation 1 [24].

$$m_v = \frac{(1+v)(1-2v)}{E(1-v)} \quad \ldots (1)$$

where, E is elastic modulus and v is the Poisson's ratio. Then, the ratio of the volumetric compressibility of the surrounding soft soil to the volumetric compressibility of the GCP material can be expressed as in Equation 2.

$$\frac{m_{vs}}{m_{vc}} = \frac{E_c(1+v_s)(1-2v_s)(1-v_c)}{E_s(1+v_c)(1-2v_c)(1-v_s)} \quad \text{... (2)}$$

where subscript *s* represents the surrounding soft soil while subscript *c* represents the GCP material. Since $v_s = v_c$, Equation 2 can be modified as shown in Equation 3. As such, it can be concluded that volumetric compressibility ratio mainly depends on the elastic modulus of GCP material and surrounding soft clay.

$$\frac{m_{vs}}{m_{vc}} = \frac{E_c}{E_s} \quad \text{... (3)}$$

The analyses were carried out for three volumetric compressibility ratios of 10, 15 and 25 under each permeability ratio. The effect of volumetric compressibility of the GCP material was studied by examining the variation of pore water pressure with respect to time, as shown in Figure 4.

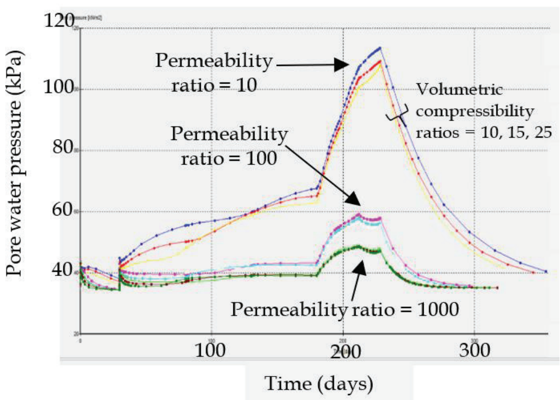

Figure 4 - Variation of pore pressure over time for different volumetric compressibility ratios

It can be seen that the effect of the volumetric compressibility ratio on the development of pore water pressure is insignificant compared to that of the permeability ratio. Although there is a slight change in pore water pressure with respect to the volumetric compressibility ratio (stiffness ratio) under low permeability ratios, this variation does not significantly affect the stability. This behaviour clearly indicates that the permeability is more significant on the stability than the stiffness of the GCP material.

4.1.3. Factor of Safety

For GCP materials with permeability ratios of 10, 100, and 1000, and volumetric compressibility ratio of 25, calculations were performed to find the Factor of Safety (FOS) using the curves developed by Matsuo and Kawamura [25] as illustrated in Figure 5. Settlement and lateral displacement of the GCP improved ground due to embankment construction were determined by selecting two points, namely A and B, as shown in Figure 1. The point A is at just under the embankment at the centre to find settlement (*S*) whereas point B is at the toe of the embankment to estimate the lateral displacement (*L*). Based on the analyses, it can be observed that as the permeability ratio increases, the FOS also increases as illustrated in Table 5. This is because a higher permeability ratio leads to higher pore water dissipation, which in turn increases the stability of the embankment.

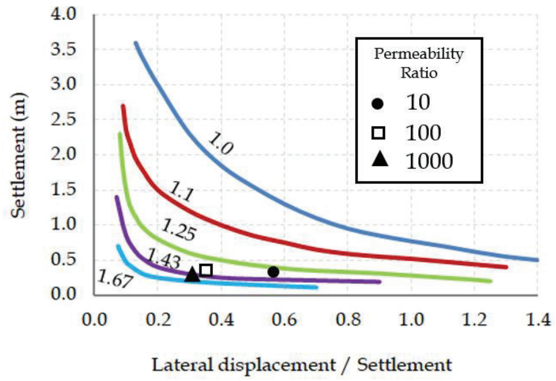

Figure 5 - Variation of Factor of Safety over permeability ratio using Matsuo and Kawamura method [25]

4.2. Effect of Surrounding Confining Pressure on Stability of GCP

Generally, the most probable failure mechanism in GCP is bulging [7][17]. The confining pressure induced by the surrounding soil helps to reduce the bulging of GCP. However, if the surrounding soil is weak, it may not provide sufficient confining pressure, which may cause GCP to fail under heavy embankment loads. Guetif et al. [26] reported that stiffness of surrounding soft soil is the main factor that affect the confining pressure. Therefore, the effect of surrounding confining pressure on the stability of GCP improved ground has been studied by varying the stiffness using the developed Unit Cell model.

The reason for the use of unit cell model in this analysis is that the material constitutive model used for soft soil differs from the plane strain model. To analyze the effect of soft soil stiffness, the relevant material model must include that parameter as an input. In the Soft Soil (SS) constitutive model which was used in OCH – Northern section 1 numerical model, there is no input for stiffness. However, in the unit cell model, the Hardening (HD) model was used as the material constitutive model for soft soil, which includes stiffness as an input parameter.

Table 5 – Calculation of factor of safety

Permeability ratio	Volumetric compressibility ratio	Settlement S (m)	Lateral displacement L (m)	L/S ratio	FOS
10	25	0.301	0.177	0.59	1.30
100	25	0.286	0.095	0.33	1.41
1000	25	0.283	0.086	0.30	1.43

The variation of lateral displacement of GCP over time for different stiffness of surrounding soil is illustrated in Figure 6. It can be seen that, when the surrounding soil is very soft with low stiffness, larger lateral displacement of GCP can be observed. In order to overcome this issue, many researchers have proposed to encase the GCP using geosynthetics especially when the surrounding soil is very soft [10-12][14-18]. Then performance of the geotextile encased GCP was analysed with respect to lateral displacement as illustrated in Figure 7. The effect of the stiffness of the geotextile on lateral displacement is also presented in the same figure. In this analysis, the stiffness of peaty clay was kept as 500 kN/m² to represent the weak nature of the surrounding soft soil.

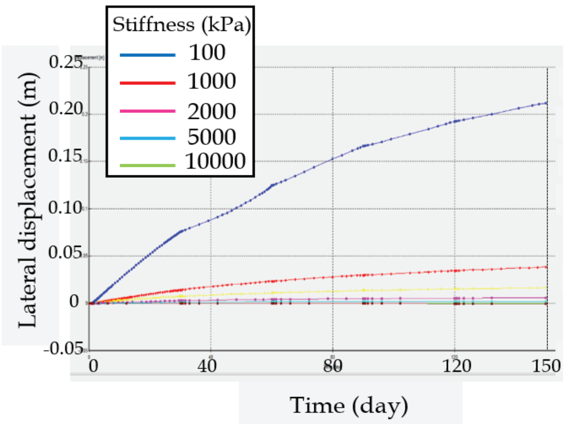

Figure 6 - Lateral displacement over time for different stiffness of soft soil

It can be seen that there is a significant reduction in lateral displacement at shallow depths when GCPs are encased with geotextile. The reason for this behaviour is that the geotextile encasement serves as the GCP's radial confining reinforcement, acting as a barrier to lateral soil movement. At shallow depths, lateral displacement is very small, especially when the stiffness of the geotextile encasement exceeds that of the GCP material. This is because, according to Murugesan et al. [15], increasing the stiffness of the geosynthetic encasement mobilizes more lateral stresses in the GCP. It can be noted that the use of geotextile encasement greatly decreased lateral movement and enhanced ground stability. In addition, the behaviour of the GCP for different stiffness values of the surrounding soil follows the same pattern when analysing lateral displacement versus depth.

4.3 Effect of GCP Length on Stability of GCP Improved Ground

When improving the soft ground using GCP, the determination of maximum GCP length that can be tolerated without compromising the performance of the GCP is crucial. However, there are no universal strict guidelines for determining this length, as such the decision depends on experience of the designer. Consequently, in certain cases, the longer length of the GCPs causes GCP improved embankments to fail [8]. Therefore, constructing GCPs longer than the critical length is neither economical nor effective. This raises a question about determining the critical length of GCPs.

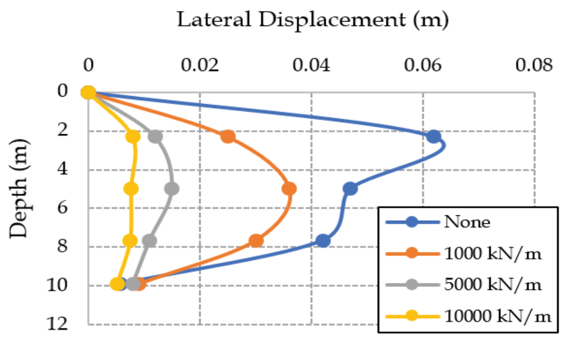

Figure 7 - Lateral displacement over depth for different geotextile stiffnesses

In this study, GCP lengths were varied from 6 m to 21 m, and the results were analysed to determine the critical GCP length for the soft ground improvement. The OCH - Northern section 1 model was used for this analysis. The typical deformation pattern of the GCPs under embankment loading after preloading period is illustrated in Figure 8. It can be seen that there is a significant lateral displacement in GCPs at the toe than that of the center of embankment. The typical variation of lateral displacement of a GCP at the toe over time is presented in Figure 9. The lateral displacement at different depths measured from top of the GCP is also illustrated in the same figure. It can be noted that more than 80% of the total lateral displacement has occurred at the end of construction.

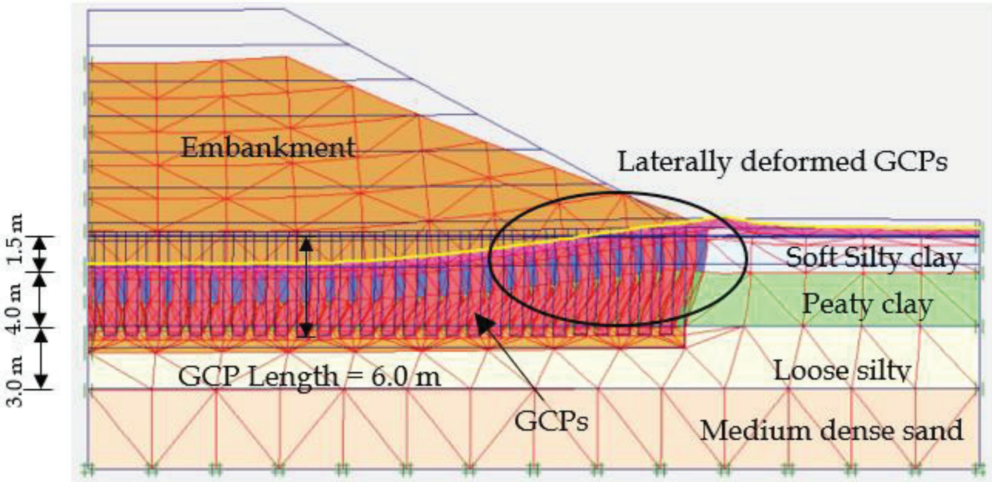

Figure 8 – Typical deformation pattern of GCP improved ground

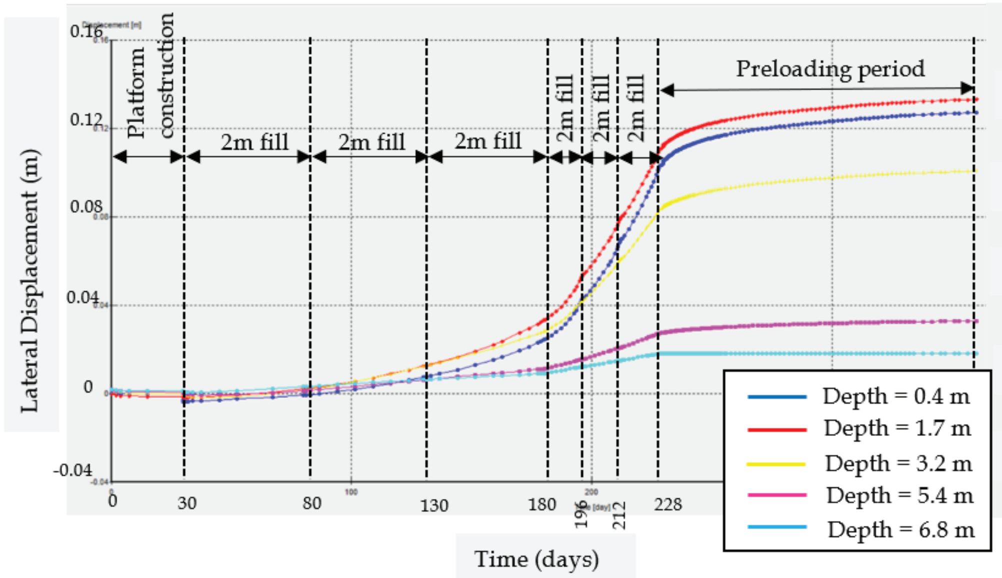

Figure 9 – Typical variation of lateral displacement over time for 6.0 m length GCPs

Table 6 – Variation of FOS versus GCP length

GCP Length (m)	Settlement (S) m	Lateral Displacement (L) m	$\frac{L}{S}$	FOS based on Matsuo and Kawamura method [25]
6	0.329	0.127	0.386	1.385
9	0.497	0.215	0.433	1.250
11	0.615	0.261	0.424	1.207
13	0.745	0.312	0.419	1.175
15	0.866	0.348	0.402	1.138
17	0.986	0.384	0.389	1.119
19	1.098	0.396	0.361	1.100
21	1.238	0.413	0.334	1.087

This is further confirmed that most critical point in the embankment construction is at the end of construction. The figure clearly shows that significant lateral displacement has occurred only down to a depth of 5.0 m. In order to further verify this evidence, lateral displacement at the toe of the embankment against depth for different GCP lengths were plotted as shown in Figure 10. It can be seen that higher the GCP length, greater the lateral displacement irrespective of the depth. Further, it can be noted that, irrespective of the GCP length, maximum lateral displacement is recorded between 0 – 5.0 m.

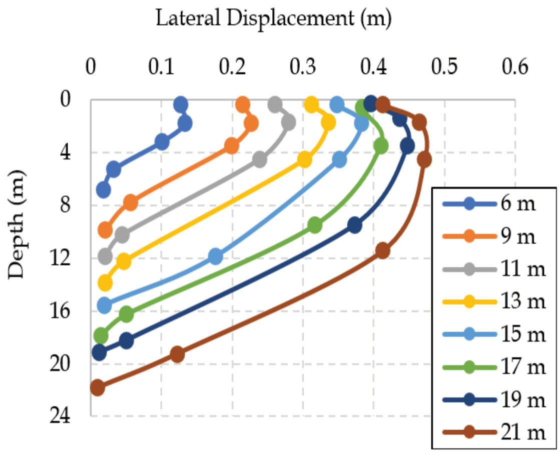

Figure 10 - Lateral displacement over depth for different GCP lengths

In order to determine the maximum safe GCP length, FOS values of GCP improved ground were estimated using Matsuo and Kawamura method [25] as illustrated in Table 6. It can be seen that FOS decreases with the GCP length. According to ICTAD Publication No. – SCA/5, 2009 [27], FOS should be greater than 1.2 for short term stability of embankments. Since short term stability implies the stability during construction, it can be concluded that safe maximum length of GCP for ground improvement in very soft soil is about 11-12 m. This was confirmed by Nekasiny et al. [8] that GCP improved embankment failed during the Southern Expressway Construction Project from Matara to Beliatta (Section 1) due to 16-18 m long GCPs.

5. Conclusions

This study investigates a large-scale expressway in Sri Lanka using local geomaterials, unlike most existing models, which are largely hypothetical, generic, and based on different locations and ground conditions. By incorporating material properties into validated numerical models, the study captures the actual behaviour of the GCP-improved ground under local conditions. The findings provide new insights into its performance and offer practical guidance for the design and assessment of similar GCP-improved grounds.

In order to understand the exact behaviour of GCP improved ground, parametric analyses were carried out using two numerical models namely OCH – Northern Section 1 Plane Strain model developed by Fernando et al. [19] and Unit Cell model developed by Alkhorshid et al. [10]. Both models were validated using the data collected from actual projects and existing literature before being used for the parametric analyses. Based on this research study, the following conclusions can be drawn:

1. Higher the permeability of GCP material, higher the stability of GCP improved ground.
2. To get the maximum benefit of the GCP improved ground, permeability of the GCP material should be greater than two orders of times that of surrounding soft clay. In other words, it is very much effective to set the permeability ratio more than 100 in GCP improved ground.
3. The permeability of GCP material is more significant than the stiffness when the stability of the GCP improved ground is considered.
4. The lateral displacement of the GCP improved ground can be significantly reduced when GCPs are encased with geotextile.
5. Irrespective of the GCP length, maximum lateral displacement is observed down to a depth of 5 m. Hence, slip surface will be developed down to a depth of 5 m and shallow rotational type failures can be expected in the GCP improved ground.
6. The safe maximum length of GCP for ground improvement in very soft soil is about 11-12 m. If the soft soil thickness is more than 12 m, it is recommended to adopt reinforcing methods to transfer the structural load to underlying hard stratum rather than ground improvement.

The results highlight several limitations of the study. In particular, the use of 2D numerical models may not fully capture 3D effects and complex interactions in actual field conditions. Material properties are mostly site-specific, which may limit the direct applicability of the results to other locations. Additionally, the parametric analysis was limited to specific conditions, and other possible configurations were not considered.

Based on the findings, several recommendations can be made. Future research should explore 3D numerical models to capture more realistic stress distributions and interactions. Furthermore, additional studies could consider a wider range of GCP configurations, spacing, and reinforcement methods to optimize performance for different site conditions. It is also recommended to apply the above conclusions in field conditions to verify these findings, including the use of geotextile encasement.

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