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Foundation Settlement in Reclaimed Mangrove Swamplands: *A Case Study of Eastern Bypass, Port Harcourt, Nigeria*

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Abstract

Useable land is scarce in the mangrove swamps of the Niger Delta. This is because it is underlain at the top by very soft to soft fibroitic silty and sandy clay (locally called Chikoko) and subject to diurnal submergence by tidal flow, thus making it difficult to develop without improvement. Reclamation by hydraulic sandfill is the commonest approach to transform such mangrove swamp areas into useable land but the ground response to sandfill placement and requirements for subsequent use are not fully understood. The purpose of this paper is to analyze the ground response to loading through settlement analysis of *insitu* CPT and laboratory data using the case study of the Eastern Bye-pass, PortHarcourt which was reclaimed in 3 phases, (1980-92, 1992-2000 and 2000-2020). The first was inspired by the necessity for a link road between Marine Base and Ogbunabali while the two subsequent phases were necessitated by strategic development needs. Reclamation involved the transformation of some 3 km^2 mangrove swamp through the placement of approximately 2.5 m thick hydraulic sandfilling over the fibrotic and bioturbated silty and sandy clay soil rich in partially decomposed vegetal matter. Although 97% Consolidation settlement was to be achieved in 3 years, the road link was constructed before the end of the 3rd year and has since been in satisfactory operational use, mainly due to the combined action of frictional bearing capacity, immediate settlement and drainage qualities of the river sand used as fill and also of the rapid settlement of the mangrove swamp soil occasioned by enhanced drainage from bioturbation.

Keywords: *Reclaimed land, settlement, mangrove swamp, Niger delta*

Introduction

As the world's population continues to increase and rural urban migration on the rise, there is increased pressure on land in most urban cities in coastal areas, particularly those close to mangrove swamps (Abam and Okagbue 1993). This pressure has led to the reclamation of extensive swamp lands which are unsuitable for development in their original condition. Land reclamation has become imperative because usable land is a premium in the Niger delta, a low lying and periodically submerged area comprising of soft and compressible sediments. This is due to a combination of socio-economic and physical factors including: population growth, industrialization demands, vulnerability to flood of the relatively low elevation of the region with respect to surface water level and wide spread occurrence of compressible sediments. Extensive areas of swamp land are therefore periodically reclaimed by Hydraulic sand-fill, dredged from surrounding rivers and creeks.

The term land reclamation has also been used for restoring an area to a more natural state after degradation or pollution or salinization has made it unusable. Land reclamation is sometimes referred to as Land rehabilitation and described in broader terms as the process of cleaning up a site that has sustained environmental degradation, such as strip mining. This can be done to allow for some form of human use such as a housing development or to restore that area back to its natural state as a wildlife habitat home.

Land reclamation has been driven essentially by the rising demand for more land as the population increases to meet the needs of building more homes in private and public housing estates recreational facilities for the growing population, expanding commercial and industrial activities and transport needs, the latest of which include roads, expressways, port and airport facilities. Reclaimed lands also serve for recreational activities. Population connectivity has been increased by building bridges and roads on reclaimed land.

The commonest method of land reclamation is the landfill. In the early years, the fill materials evacuated from the land based borrow were used for filling the reclamation areas. In recent years, sea and river sand is the main source of fill materials for reclamation. In some cases, as in Singapore, reclamation contractors import the needed sand from the neighboring countries such as Indonesia (Guangqing et al., 2021). Even eroding beaches have been repaired or restored through using materials such as sand from inland sources. Although this may not serve as a long-term solution, it is cheap compared to other types of coastal defenses. Sand materials may also be dredged from seabed. In Singapore, sand from the seabed and construction waste soils was used for land reclamation for the development of sea ports (Wikipedia: https://en.wikipedia.org/wiki/Land_reclamation_in_Singapore) .

Construction over newly reclaimed land carries considerable challenges and risks due to the dynamic nature of the environment (Chun et al., 2019). Progress with construction can be hindered due to the possibility of unexpected large consolidation settlements from large buildings or storage tanks (Shahin 2010, Mesri and Funk, 2015; Wei-Qiang et al., 2021). Following observation of settlement patterns, Abam and George (2004) recommended the sequence of preloading during the construction of large storage tanks based Asaoka (1978). Based on similar settlement observation, Wei Rulong (1993) derived coefficient of consolidation. Abam and Ofoegbu (2000) described foundation construction procedures needed to prevent failure in reclaimed mangrove swamps. Excessive settlement of soft soil may often lead to engineering accidents and is harmful to the operation of airports, for example the famous case of Kansai International Airport in Japan (Yoichi and Shinji , 2016), where the settlement of the foundation far exceeds the expectations of geotechnical experts. With the rapid development of airport construction in China, the settlement of reclamation soil foundation of airports has been a limiting problem for the construction schedule due to the existence of saturated soft soil with high void ratio on the seafloor. The total settlement of soft soil layer under external loads can be divided into instantaneous settlement, primary consolidation settlement, and secondary consolidation settlement. It is for this reason that the settlement of soft soil foundation is considered a critical problem for civil developments in coastal area (Guangqing et al., 2021).

Due to lack of understanding of the ground response to the placement of fill, such reclaimed areas are hardly used within the lifetime of the government responsible for the reclamation. Often, ground improvement employing surcharge and flexible drains are employed to accelerate the ground settlement (Leung et al., 2019). The settlement process of soft soil like silt layer under the external loads of structures is complicated and hard to be predicted in practice (Guangqing Liu et al., 2021). The instantaneous settlement can be completed once the loads are applied, therefore, it has little effect on the sequent settlement after the structures or runway of airport is constructed. Many researchers have studied the soil consolidation based on the classical soil mechanics (Li et al., 2021; Adejumo and Boiko, 2014). In fact, what may have an impact on the project are the primary consolidation settlement and the secondary consolidation settlement, which will take a long period to complete.

Because the process of land reclamation destroys natural landscapes, it has been associated with several environmental issues (Yu and Zhang, 2011). It can result to habitat destruction causing loss of biodiversity and fisheries. There are also reports that land reclamation causes flooding (Jiang, 2008); (Andrzej, 2020) and can have potentially disastrous consequences. If it takes place too quickly, the nature would not adapt to it.

Land reclamation has played a significant role in the urban development process in many coastal areas in the world. While reclamation provides valuable land, it also creates various coastal engineering, environmental and marine ecological problems. These problems directly caused by reclamation have been well recognized and widely studied. However, it has not been recognized yet that reclamation will almost certainly change the regional groundwater regime, in turn causing similar problems (Jiu 2008).

The Mangrove swamps are widely considered as both economic as well as an ecological resource. This is apart from the environmental services of providing a windshield and protection against flood and storm surges, fish nursery and local construction material for proximal communities (NDES 1999). These benefits are traded off whenever Mangrove swamps are eliminated through their reclamation. No doubt, many of the decisions to reclaim Mangrove swamps hardly consider the environmental economics of the alternative services that they provide. It is also seen that the reclamation may impact the ground water regime near the coast. It has been demonstrated that large-scale reclamation will increase groundwater level, modify the groundwater divide, and alter submarine groundwater discharge to the coast (Peng et al., 2021; Cong et al., 2018). The change of groundwater conditions will cause engineering and environmental problems by modifying the infiltration capacity, flooding pattern, stability of slopes and foundations, interface between seawater and groundwater, and the coastal marine environment. Fettweis et al., (2010) reported very high SPM concentration near the bed during the dredging procedures. Such a high concentration of SPM has been cited as the reason for the degradation of the quality of water during dredging in the Lagos lagoon. The resultant turbidity levels in the lagoon were slightly higher than the allowable limits for discharge to marine environment set by the Law.

Consolidation analysis is a key task for reclamation design. Although consolidation is a long-term process, acceleration of consolidation is often preferred for speeding up the reclamations. Before proposing measures to accelerate the consolidation and reclamation process, it is imperative to have an accurate prediction of consolidation settlement for fine-grained materials, which is greatly affected by the spatial distribution of subsurface zones with different soil types (i.e., stratigraphic heterogeneities and uncertainty) and spatial variability of soil properties. In current practice, the calculation of consolidation settlement often uses simplified stratigraphic boundaries and deterministic consolidation parameters without considering stratigraphic uncertainty or soil property spatial variability

(Chao and Wang 2022). The oversimplified practice might result in unconservative estimations of consolidation settlement and pose threats to safety and serviceability of constructed facilities on reclaimed lands. Consequently, the objective of the study is to determine the timing for utilization of reclaimed mangrove swamp lands for development through a case study of Eastern Bye-pass in Port Harcourt. The paper also explores the possibility of pre-compression to minimize post construction settlement in soft soil.

Site Description and Geology

The Mangrove swamps cover an area of about 1,900 km^2 and constitute the dominant wetland ecosystem in the Niger Delta region. Mangrove swamps occur between the Quarternary sediments of the Meander belt and the Barrier Island (Fig. 1) in areas dominated by a network of tidal creeks and subject to diurnal tidal inundation with the highest tidal registration of 2.62 m while the lowest remains 0.31 m and tidal range averages 1.52 m. The study location which has been cleared preparatory for sandfilling (Fig.2) was previously vegetated by Mangrove forest. In the course of time, the mangrove vegetation was invaded by Nypa Palms which substantially displaced the original mangrove vegetation. The progress and success of Nypa Palm in the area has been partly due to urbanization /developments which considerably reduced saline influx and influence on the area. The Quaternary sediments give rise to alluvial plains. The alluvial plains include the estuarine sediments, which are under the influence of tidal brackish waters along the coast and in the estuaries of rivers and creeks.

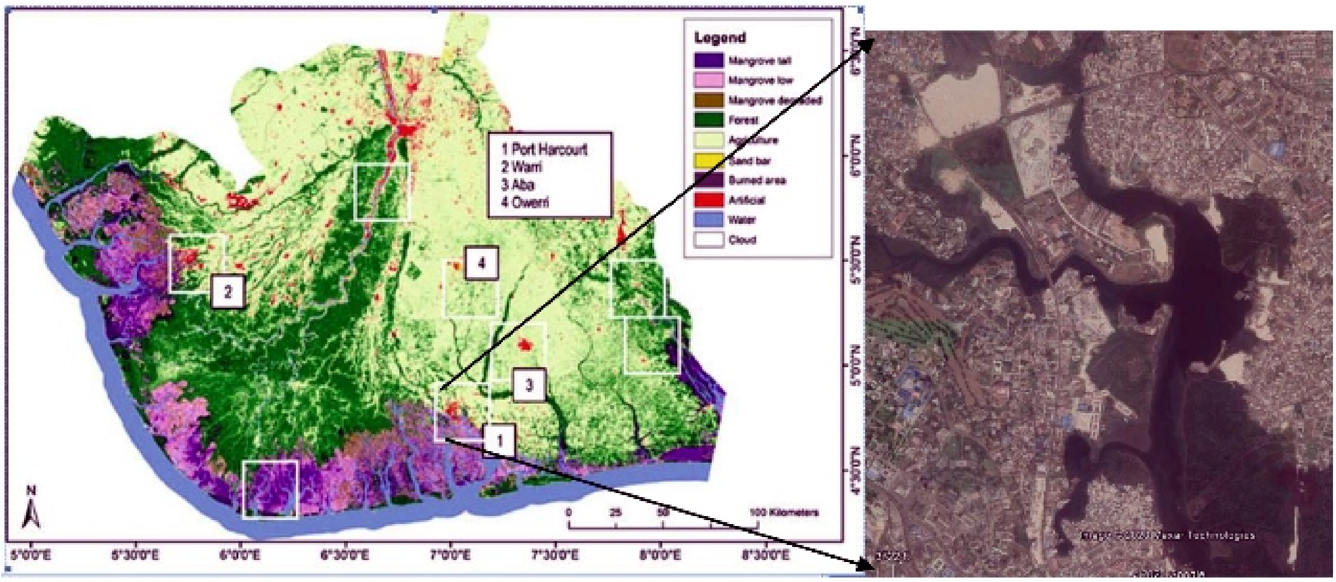

Fig. 1: Imagery of Case study Site and Relative positions of test points

The Mangrove swamp consists of very soft and weak Quaternary sediments with composition within the silty and sandy clay window. Mangrove swamps constitute a veritable habitat for interval species and habour burrows created by bioturbation which enhance their permeability and drainage characteristics. As

Fig. 2: Site conditions of swampland after cutting and stumping of mangrove vegetation to allow access for field testing

foundation layers they present serious concerns of shear failure and excessive settlement. However, due to high field permeability, laboratory oedometer based tests usually overpredict settlements.

Materials and Methods

Five locations within the Eastern Bypass were investigated, namely; the Scripture Union premises in Marine Base, the NDDC regional office complex, 2 sites at Ogbunabali and Nkpogu (Groundscan 2019). Each of these sites has been reclaimed by sandfilling and are considered as adjoining the Bonny River estuary. The main focus of the investigation was to determine the settlement characteristics of the site. Intrusive investigations involved 8 no. borings and 6 no. CPTs followed by laboratory analysis. Classification, strength and compressibility tests were also carried out on retrieved soil samples from the boreholes. Fig (3) shows the layout of the test points.

A vertical depth profile of the undrained strength and Bearing Capacity of the swampland was obtained from Cone Penetration Tests results based on the well-established equation of Tomlinson (1999) and Bowles (1997):

$$Cu = \frac{q_c - \sigma'}{N_k} vo \quad \text{...(1)}$$

Where

qc - σ' = net cone resistance

N_k = Cone factor

While bearing capacity was evaluated using Meyerhoff (1976) equation: The essence of determining the bearing capacity of the swampland was to evaluate the maximum thickness of fill to be placed on the natural ground at a time without the risk of shear failure. Settlement of foundation was predicted for a net foundation load of Ds = 100kN/m^2 using the relationships:

$$S = m_v . \Delta\sigma . H_o \quad \text{...(2)}$$

Where s = total settlement

Ho = thickness of compressible layer

m_v = coefficient of volume compressibility

Ds = increase in vertical stress due to applied pressure

The increase of vertical stress at depth (Z) was based on the assumption that the stress from the foundation spreads out along lines with a 2 vertical to 1 horizontal slope governed by the equation:

$$\Delta\sigma = \frac{q_o \times B \times L}{(B + Z)(L + Z)} \quad \text{...(3)}$$

Where B and L are breath and length of foundation.

This vertical stress distribution is graphically represented by Figure (4):

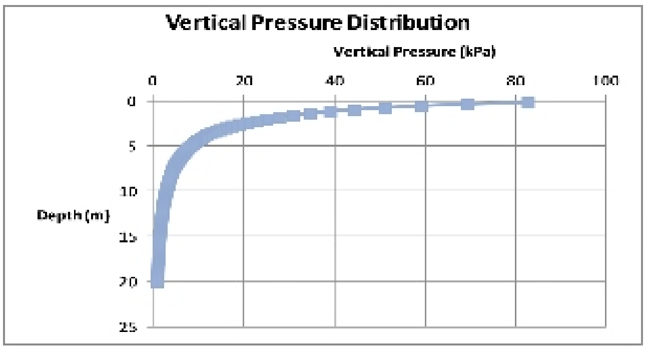

Fig. 4: Graphical representation of vertical stress distribution

Results of the Cone Penetration tests was used directly to predict the possible settlement of a foundation placed on the soil tested using the method proposed by de Beer and Martens (Smith and Pole, 1980) in which Constant of compressibility is given by,

$$C_s = \frac{1.9C_r}{P_{01}} \quad \text{.. (4)}$$

Where Cr = static cone resistance (kN/m^2)
Po_1 = effective overburden pressure at point tested.

Total immediate settlement,

$$S_{pi} = \frac{H}{C_s} \log e \frac{P_{o2} + \Delta\sigma_z}{P_{o2}} \quad \text{..(5)}$$

Where $\Delta\sigma_z$ = vertical stress increase at the center of the consolidating layer of thickness H.
Po_2 = effective overburden pressure at the center of the layer before any excavation or load application.

Prediction of the settlement is then made from the summation of the vertical strains caused by the sandfill load. In effect, the soil beneath the foundation was divided into thin layers and the coefficient of volume compressibility m_v computed for each layer. The swampland is to be sand filled to the depth of about 5 m. With an average of 20 kN/m^3 as unit weight, the fill will result to roughly 100kN/m^2 of incremental vertical load.

Rate of Settlement was evaluated using the relationship $T_v = C_v\ t/(H^2)$, which when re-arranged resulted in t(years) = T_v*H^2/Cv. For 90% degree of consolidation, the Time factor Tv = 0.848 and with sand-fill at the top of the swampland, double drainage was assumed. The time for various percentage consolidations was computed based on a 2-way drainage path.

The effect of preload was modeled by assuming the placement of additional surcharge over the sandfill on the ground which will then result in a primary consolidation settlement given by:

$$S_{c(p+f)} = \frac{C_c H_c}{1 + e_o} \log \frac{\sigma'_o + [\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}]}{\sigma'_o} \quad \text{.................... (6)}$$

The total settlement of Sc(p) will occur at time t_2, which is much shorter than t_1. Hence, if a temporary total surcharge of Δσ'(p)+Δσ'(f) is applied on the ground surface for time t_2, the settlement will be equal to Sc(p). At that time, if the surcharge is removed and a structure with a permanent load per unit area Δσ'(p) is built, no appreciable settlement will be expected to occur. The total surcharge Δσ'(p)+Δσ'(f) can be applied by means of temporary sand fills.

The degree of consolidation at time t_2 (which is actually the average degree of consolidation at time t_2) under the application of a surcharge of Δσ'(p)+Δσ'(f) is given as:

$$U = \frac{S_{c(p)}}{S_{c(p+f)}} \quad \text{..(7)}$$

By substituting Eq(5) and Eq(6) in Eq(7) we get:

U

$$U = \frac{\log\left[\frac{\sigma'_o + \Delta\sigma'_{(p)}}{\sigma'_o}\right]}{\log\left[\frac{\sigma'_o + \Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}}{\sigma'_o}\right]} = \frac{\log\left[1 + \frac{\Delta\sigma'_{(p)}}{\sigma'_o}\right]}{\log\left\{1 + \frac{\Delta\sigma'_{(p)}}{\sigma'_o}\left[1 + \frac{\Delta\sigma'_{(f)}}{\Delta\sigma'_{(p)}}\right]\right\}} \quad \text{............(8)}$$

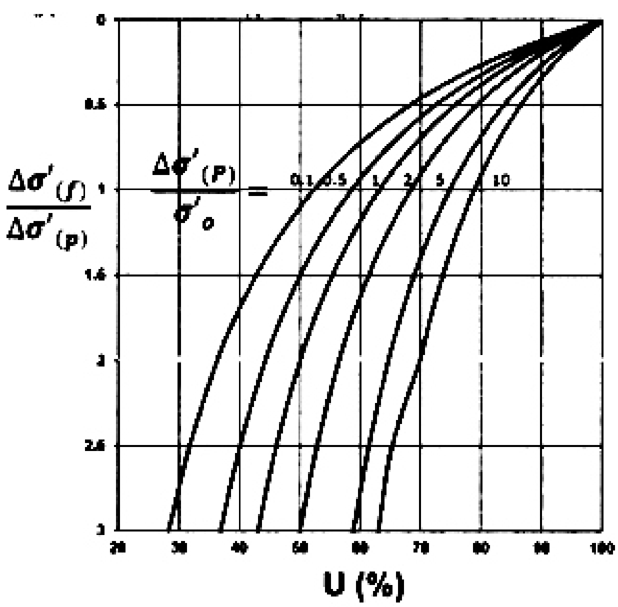

Fig. 6: Variation of magnitudes of U for combinations of Δs ’(p)/ s ’o and Δs ’(f) / Δs ’(p).

After U is obtained, the corresponding Time factor Tv is derived and substituted into the equation:

$$\mathbf{T_2 = Tv{*}H^2/C_v} \quad \text{..(9)}$$

to derive t_2.

The time t_2 which is less than t_1, is the time to attain an equivalent settlement under the preload or surcharge.

Results and discussion

The data from the soil boring, sampling and laboratory tests were carefully evaluated for the determination of the stratification of the underlying soils. The composite stratigraphy from the boreholes across the reclaimed land is presented in Fig (7)

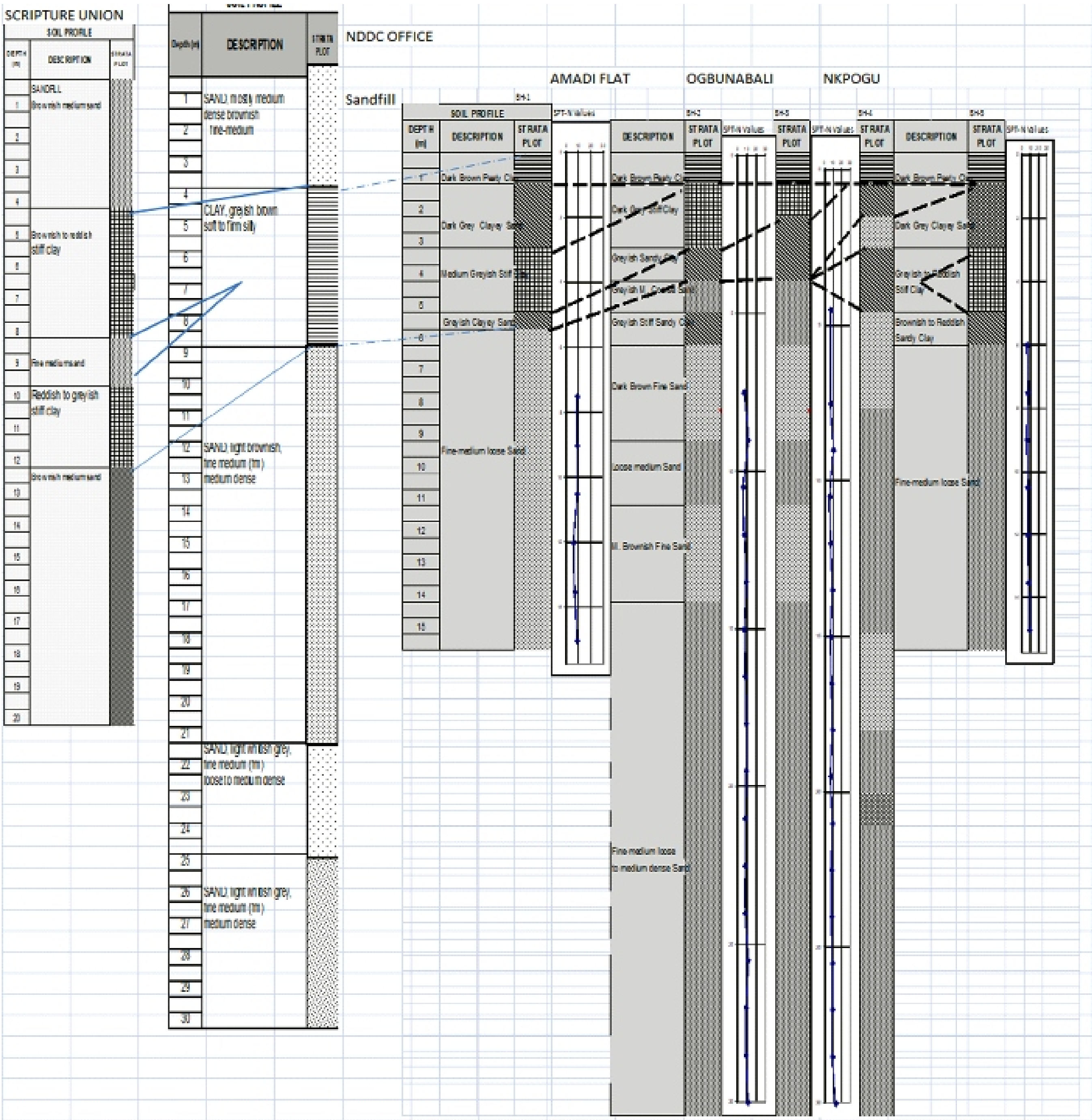

Fig. 7: Stratigraphy of soils from Marine Base-Ogbunabali-Nkpogu Mangrove swamp

The stratigraphy shows a top organic soil (maximum of 1 m thick) followed by silty sandy soils extended to maximum depth of 6 m followed by a monotonous mostly loose sand layer. The sand is free draining with coefficient of permeability averaging $1x10^{-3}$ m/s and mostly loose to medium dense in relative density (Groundscan 2019). The Water table is at the ground surface as site is inundated at high tide. Classification, strength, and compressibility characteristics of the soils determined from laboratory are summarized in Tables (1 to 3).

Table 1: Soil properties of cohesive layer at NDDC Office Complex, Marine Base Eastern Bypass, Rivers State

BH No.	Depth (m)	Moisture Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Liquidity Index	Compressibility (Cc)	Swell Potential	Coeff of Earth Pressure (Ko)
1	4.5	84	68	20.5	47.5	1.34	0.52	26.64	0.64
	6	25	65	19.6	45.4	0.12	0.50	23.86	0.63
	7.5	22	59	19.6	39.4	0.06	0.44	16.88	0.61
2	4.5	23	67	20.4	46.6	0.06	0.51	25.43	0.64
	6	22	39	14	25	0.32	0.26	5.56	0.55

Table 2: Summary Geotechnical Properties of Swampland Amadi flat-Ogbunabali-Nkpogu

BH No.	Depth (m)	Moisture Content (%)	Unit Weight (kN/m^3)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Coeff of Earth Pressure (Ko)	Undrained Cohesion kN/m2	Angle of Internal Friction(Deg.)
1	3	30.9	18.3	38.5	20	18.5	0.518		
	4.5	35	17.8	53.5	28	25.5	0.547	100	21
2	3	24.7	19.4	52	22	30	0.566	58	22
	6	16.7	20.4	47.2	34	13.2	0.495	140	23
3	1.5	30.9	18.3	48	33	15	0.503	70	22
	4.5	16.3	21	46	31	15	0.503	79	25
4	1.5	21	17.9	65.5	35	30.5	0.568		
	4.5	21.3	19.9	21	16	5	0.461	98	18
5	3	17.7	20.5	32	19	13	0.495	58	19
	4.5	16	20.8	35	16	19	0.520		

Table 3: Geotechnical Parameters for Cohesive Layers at Amadi flat-Ogbunabali-Nkpogu

BH No.	Depth (m)	Effective Thickness (M)	Moisture Content, %	S.G	Bulk Density, kN/m^2	Cc	Voids Ratio	Mv (m^2/MN) x10-5	Cv (m^2/yr) x102	kv (m/s) x10-10	Settlement (mm) from Clay layers
1	3	3	27.90	2.57	21.8	0.06	0.412	0.31	2.12	2.04	60.023
	4.5	2.5	33.42	2.61	18.7	0.09	0.4	1.61	1.22	6.24	54.662
2	3	4	24.70	2.59	18.9	0.07	0.463	2.19	1.32	8.17	84.495
	6	2	19.10	2.58	23.6	0.06	0.246	0.34	18.42	19.22	25.512
3	1.5	2.5	30.50	2.71	17.1	0.34	0.582	3.49	1.21	13.55	370.774
	4.5	1.5	16.50	2.62	19.2	0.09	0.359	4.41	1.37	13.47	33.172
4	1.5	2	21.15	2.63	17.3	0.49	0.663	3.52	1.82	16.60	404.293
	4.5	3	19.05	2.58	19.4	0.08	0.3	2.13	1.24	8.20	61.204
5	3	3	18.00	2.6	18.6	0.12	0.653	6.21	1.38	24.30	97.118
	4.5	3	16.90	2.58	24.2	0.02	0.164	0.36	23.88	27.00	16.344

Results of the computed time for 90% consolidation are presented in the summary Table (4). The time to attain various degrees of consolidation settlement after placement of fill were also calculated (Table 5). Additional settlements that might arise as a result of the placement of preloading for precompression purposes (additional sandfill) of various heights were examined and resultant settlement predicted. The predicted Settlement for various preloading options are presented in Table (6). The values of the additional settlement would be the recorded values less those predicted for proposed fill height of 5 m. Results show that the settlement with different preloading durations under the same thickness of soft soil is different. As the preloading duration increases, the total settlement in the same period becomes smaller. The time required for 100% Settlement for different preloading options are presented in Table (7).

Total Consolidation Settlement (Table 8) ranged from 110 mm to 471 mm in the boring locations at the Nkpogu section of the reclaimed Mangrove swamp for a vertical incremental load of 100 kN/m^2, equivalent to 5 m of sand-fill. Predicted consolidation settlement for different sand fill heights in mangrove swamps are summarized in Fig. 8. This shows that total settlement has an approximately linear relationship with fill or surcharge thickness.

The concern for potential shear failure is limited to the top 2 m, which if carefully handled will eliminate any prospect of failure due to loading and placement of

Table 4: Spatial Distribution of Consolidation Settlement at Borehole Locations

BH No.	Depth (m)	Effective Depth Range (m)	Effective Thickness (m)	Mv (m^2/MN)	Cv (m^2/yr) x102	kv (m/s) x10-10	Settlement (mm) from Clay layers	Sum of Settlement from clay layers	Settlement from sandy layers	Total Settlement (mm)	Time in Years for 90% Consolidation
1	3	0-3	3	0.31	2.12	2.04	60.023	114.684	2.05	116.734	3.840
	4.5	3-5.5	2.5	1.61	1.22	6.24	54.662				
2	3	0-4	4	2.19	1.32	8.17	84.495	110.007	2.97	112.977	4.827
	6	4-6	2	0.34	1.842	19.22	25.512				
3	1.5	0-2.5	2.5	3.49	1.21	13.55	370.774	403.946	4.88	408.826	2.629
	4.5	2.5-4	1.5	4.41	1.37	13.47	33.172				
4	1.5	0-2	2	3.52	1.82	16.60	404.293	465.498	6.13	471.628	3.464
	4.5	2-5	3	2.13	1.24	8.20	61.204				
5	3	0-3	3	6.21	1.38	24.30	97.118	113.462	2.67	116.132	4.051
	4.5	3-6	3	0.36	2.388	27.00	16.344				

Table 5: Time in years for various degrees of consolidation

BH No.	Depth (m)	Cv (m^2/yr) x10^2	Time in Years for 5% Consolidation	Time in Years for 10% Consolidation	Time in Years for 15% Consolidation	Time in Years for 20% Consolidation	Time in Years for 30% Consolidation	Time in Years for 40% Consolidation	Time in Years for 50% Consolidation	Time in Years for 60% Consolidation	Time in Years for 70% Consolidation	Time in Years for 80% Consolidation	Time in Years for 90% Consolidation
1	3	2.12	0.045	0.272	0.634	1.087	1.811	2.355	2.808	3.260	3.532	3.713	3.840
	4.5	1.22											
2	3	1.32	0.057	0.342	0.797	1.366	2.277	2.960	3.529	4.099	4.440	4.668	4.827
	6	1.842											
3	1.5	1.21	0.031	0.186	0.434	0.744	1.240	1.612	1.922	2.233	2.419	2.543	2.629
	4.5	1.37											
4	1.5	1.82	0.041	0.245	0.572	0.980	1.634	2.124	2.533	2.941	3.186	3.350	3.464
	4.5	1.24											
5	3	1.38	0.048	0.287	0.669	1.146	1.911	2.484	2.962	3.439	3.726	3.917	4.051
	4.5	2.388											

Table 6: Predicted Settlement for Preloading Option

BH No.	Depth (m)	Effective Depth Range (m)	Effective Thickness (m)	Settlement under present condition of 5m Fill	Settlement with Additional 1.5m Surcharge (mm)	Settlement with Additional 3m Surcharge (mm)	Settlement with Additional 4.5m Surcharge (mm)
1	3	0-3	3	116.73	137.30	154.93	170.38
	4.5	3-5.5	2.5				
2	3	0-4	4	112.98	132.91	150.05	165.10
	6	4-6	2				
3	1.5	0-2.5	2.5	408.83	465.23	511.95	551.86
	4.5	2.5-4	1.5				
4	1.5	0-2	2	471.63	538.22	593.62	641.07
	4.5	2-5	3				
5	3	0-3	3	116.13	136.02	153.01	167.83
	4.5	3-6	3				

Table 7: Time required for 100% Settlement for different Preloading options

BH No.	Present scenario of 5m fill				SCENERIO-2 (1.5m ADDITIONAL SAND PLACEMENT)				SCENERIO-3 (3m ADDITIONAL SAND PLACEMENT)				SCENERIO-4 (4.5m ADDITIONAL SAND PLACEMENT)			
	Settlement (mm)	U%	Tv	t(yrs) for 100%	Settlement (mm)	U%	Tv	t(yrs) for 100%	Settlement (mm)	U%	Tv	t(yrs) for 100%	Settlement (mm)	U%	Tv	t(yrs) for 100%
1	114.68	1.00	0.90	4.08	135.25	0.85	0.80	3.62	152.88	0.75	0.65	2.94	168.33	0.68	0.57	2.58
2	110.01	1.00	0.90	5.12	129.94	0.85	0.80	4.55	147.08	0.75	0.65	3.70	162.13	0.68	0.55	3.13
3	403.95	1.00	0.90	2.79	460.35	0.88	0.83	2.57	507.07	0.80	0.75	2.33	546.98	0.74	0.65	2.02
4	465.50	1.00	0.90	3.68	532.09	0.87	0.83	3.39	587.49	0.79	0.75	3.06	634.94	0.73	0.65	2.66
5	113.46	1.00	0.90	4.30	133.35	0.83	0.78	3.73	150.34	0.73	0.65	3.11	165.16	0.66	0.55	2.63

Table 8: Summary of consolidation settlement on swamp lands

BH No.	Settlement from Cohesive Layer (mm)	Settlement from Sandy Layer (mm)	Total Settlement (mm)
1	115	2.05	117
2	110	2.97	113
3	404	4.88	409
4	465	6.13	471
5	114	2.67	117

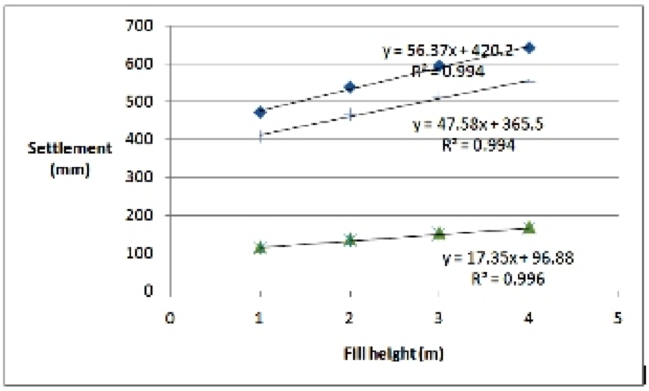

Fig. 8: Predicted consolidation settlement for different sand fill heights in mangrove swamps

sandfill on the swampland. With an undrained strength averaging 25 kPa and an Allowable bearing pressure of 60 kPa, a fill of 2 m will exert a load of 40 kPa, which is less than the allowable bearing pressure of 60 kPa.

The sandfill materials may therefore be placed in lifts of 2 m without the consequence of shear failure. The pushing by Bulldozers will accelerate the consolidation settlement of the top 2 m of compressible soils and will further compact the emplaced sand which already enjoys the advantage of immediate settlement.

Conclusions and Recommendations

The development of physical infrastructure on reclaimed swampland can hardly be successful without adequate understanding of the compressibility characteristics of the soils in the area. This exercise requires basic geotechnical data of the underlying soils within the depths of engineering significance to reclamation by hydraulic sand-fill. Although Mangrove swamps comprise of highly compressible silty and sandy clays, the presence of bioturbation enhances drainage and reduces the time to full consolidation. Due to the several concerns, dredging and reclamation projects are categorized as project requiring mandatory EIA and are restricted or no longer readily allowed, due to environmental protection laws. It is suggested that, for a major reclamation project, the change of the hydrogeological system in response to reclamation should be evaluated so that the disturbance to groundwater regimes and the damage to environment might be minimized.

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Conflicts of Interest

"The authors declare no conflict of interest.".

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