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Slope Stability and Settlement Analysis for Dry Bulk Terminal at Mozambique: A Case Study

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ABSTRACT

Stability of man-made soil slopes is an important issue for long term performance of any bulk terminal storage facilities and it becomes more critical for very heavy material storage like iron ore, coal etc. In most of the cases, it is observed that the parent (original) in-situ sub-soil formations are not capable to support such heavy bulk storage material. Hence, ground improvement techniques are usually recommended for such soft soil sites, in addition to maintain the stability of the slope of the stack itself. Present case study describes the design of three types of stacks for a proposed bulk terminal site at Beira, Mozambique for storage of iron ore and coal. The site consists of thick soft to very soft clay layers resting on inter-bedding of the sandy/silty sand layers. The geotechnical characterization was carried out through drilling 16 boreholes and conducting 9 cone penetration tests. Since the subsoil stratum was not capable enough to take the expected pressure from the bulk storage, the ground improvement is proposed in form of wick drain/strip drains in order to accelerate the consolidation and gain in strength. In order to optimize the cost and construction time, staged construction method was adopted and strength gain during each construction phase was monitored. To limit the foundation settlement and to estimate the expected lateral thrust on the reclaimed foundation; detailed slope stability analysis and settlement analysis are carried out at each construction stage. It was observed that under the 10m of stacking height of iron ore; the ground may settle more than 3m and the differential settlement of more than 1.5m may influence the stacker reclaimer foundations. Both the rotational slip failure mode and translational failure mode are checked to obtain the limiting displacement for foundation failure. Staged construction program along with safe heights for material handling in each construction stage are finally recommended based on the detailed slope stability and settlement analysis.

KEYWORDS: slope stability, settlement, ground improvement, iron ore, coal stack, soft soil, railway embankment, limit equilibrium method, numerical analysis.

INTRODUCTION

There are various types of soil slopes viz. man-made and natural. Stability of man-made soil slopes like cuttings made for embankments of highways and railways, earth dams, temporary excavations, tips and soil heaps, etc. need to be considered carefully by geotechnical engineers so that no failure of such slopes occur. Hence it is necessary to ensure the stability of the stockyard area for its safe working operation and it is very challenging especially for iron ore stockyards where the weight of the material to be stored are significantly high. The instability of such man-made stockyard slopes are usually resisted by shearing forces within the soil or the embankment material.

Koutnik et al. (2008) analyzed one typical cross section in the New Orleans area of USA and found out the factors of safety from different methods for the purpose of comparison assuming both circular and wedge-shaped failure surfaces. Authors used SLOPE/W software for slope stability analysis. It was concluded that, the actual difference in factor of safety by various methods significantly depends on the assumptions, soil properties and stratification, loading, geometry, pore water pressures.

Wei et al. (2010) presented a case study in which Spencer’s method, shear strength reduction and finite element were used to compute the factor of safety for man-made slopes. It was shown that Spencer’s method is one of the best limit equilibrium based methods that can satisfy all the static equilibrium conditions.

Stability analysis is performed for any man-made slopes using limit equilibrium method generally by using computer applications in present times. In this method shearing resistance required to maintain a limiting equilibrium condition is compared with available shearing strength on the predefined failure path. Detailed and extensive applications of simple limit equilibrium method for stability analysis soil slopes were reported recently by Choudhury and Subba Rao (2006), Choudhury et al. (2007), Choudhury (2008), Choudhury and Modi (2008), Choudhury and Nimbalkar (2009), Nimbalkar and Choudhury (2010), Verma et al. (2012), Chakraborty and Choudhury (2012, 2013) and many others. Hence in the present study both rotational (circular) and translational (non-circular) stability analysis are performed to ensure safe working operations for stockyard areas using limit equilibrium method. The factor of safety for slopes are determined by using major three methods namely, Bishop’s method, Spencer’s method and Mongersten-price’s method (see Ranjan and Rao, 2000), which are commonly used in for any slope stability analysis.

DESCRIPTION OF PROJECT SITE

For establishing a multi user coal and iron ore terminal at Beira port in Mozambique, Essar had started the project for finding the solution for stability and settlement of such proposed huge stacks. The proposed project area lies to the North of the existing Beira Oil Terminal, where a back up area has been reclaimed by PORTOS E CAMINHOS DE FERRO DE MOÇAMBIQUE (CFM) from dredged sand obtained from the dredging operation recently undertaken by CFM for deepening of the navigation channel to the Port. Figure 1 describes the location of the project site along with proposed berth locations. Figure 1 shows proposed stock yard area, existing reclaimed area and proposed berth location.

Figure 1: The proposed site location of stock yard and berth location at Beira, Mozambique

During year 2007, a broad Geotechnical investigation was carried out by sixteen boreholes with SPTs and 19 CPTs. These tests were performed at the stockyard area for proposed coal stack yard including in-situ and laboratory tests. Sample for laboratory tests were extracted by Shelby samplers. Laboratory tests include triaxial tests (CU and UU), permeability, oedometer consolidation tests, pocket vane shear tests and water chemistry tests. Vane shear test was also conducted as a part of field investigation. The overall scenario of the geotechnical condition can be captured by the variation of SPT N-values observed at the site as presented in the Figure 2. Since, scattered profiles are observed for the stockyard area, the average value was selected for further analysis. Few stockyards specific borehole data inform of SPT N-Values are plotted separately to evaluate the shear strength properties for the stockyard area and presented in Figure 3. Based on the soil investigation report, the investigating agency has proposed the worst, average and best soil profiles that could be considered further for design of foundation system and average properties are selected for preliminary evaluation of the geotechnical conditions.

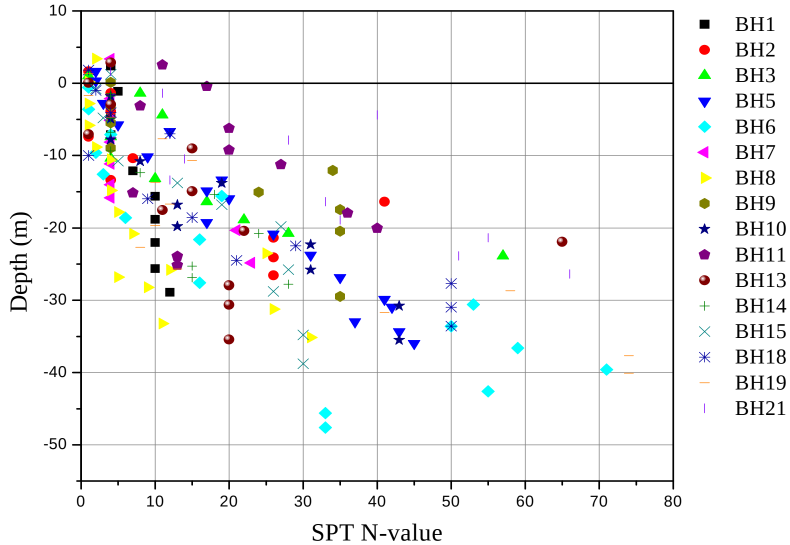


Figure 2: Observed SPT N- Values for entire geotechnical investigation at Beira

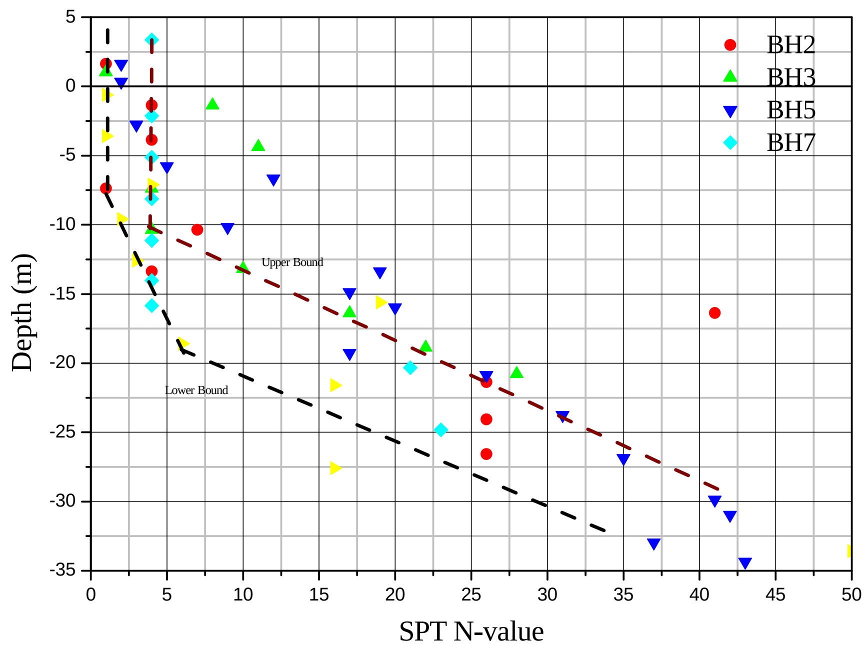


Figure 3: Observed SPT N-values for stock yard describing upper bound and lower bound values selected for the present geotechnical analysis

PROBLEM STATEMENT

It can be observed from the soil report that the geotechnical condition for top 10m to 15m is very soft. This in turns leads to the problem that, it cannot support the Iron ore stockyard and

Coal stacks on this soil. Hence, the combined stability and settlement analysis is required to be done if one wants to proceed with the same.

This paper explains the problems associated with iron and coal stacks and railway embankment constructed in Beira, Mozambique for a proposed bulk terminal. The stability analysis and settlement calculations for the iron and coal stacks are performed using software SLIDE V 5.027 and SETTLE 3D respectively.

STABILITY ANALYSIS OF IRON ORE STACK

The Iron ore stacking is to be stacked up to a height of 7.5m with Three stacks of 44 m wide are modeled with 20m spaces in between. The Iron core has been assumed to be stacked in three stages for the purpose of analysis as first 4.5m, 1.5m and 1.5m respectively. Table 1 shows the strength model and properties considered for stage I. Stage II comprises of raising another 3 m of iron ore as shown in Figure 4.

Table 1: Strength model and properties considered for all stages

Layer	**Unit wt** (kN/m^3)			**Strength Model**			**C or C$_u$** (kPa)			ϕ (degree)		
	Iron core	Earth Core	Marine clay	Iron core	Earth Core	Marine clay	Iron core	Earth Core	Marine Clay	Iron core	Earth Core	Marine clay
I	22	18	17	M-C	M-C	U	0	0	17.0	38	30	0
II	22	18	17	M-C	M-C	U	0	0	17.5	38	30	0
III	22	18	17	M-C	M-C	U	0	0	17.5	38	30	0

M-C: Mohr-Coulomb envelope
U: Undrained

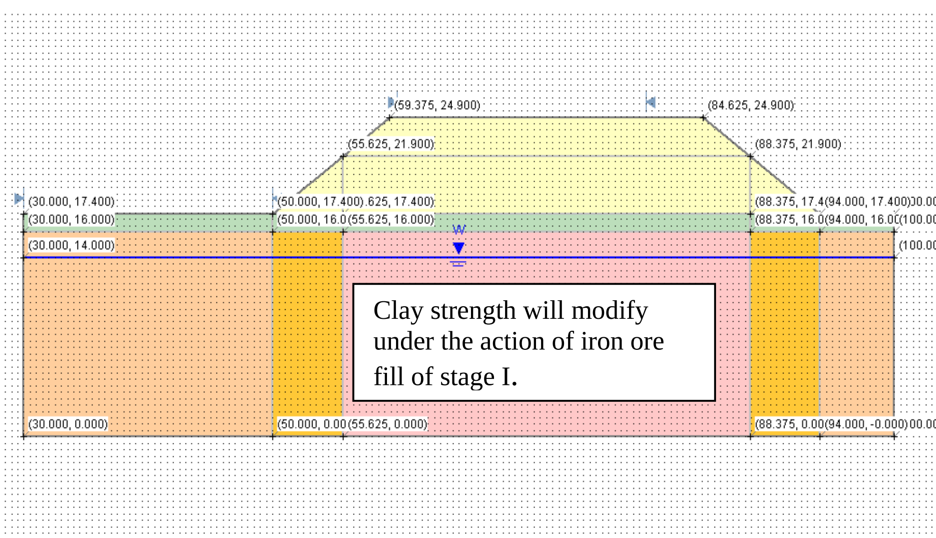
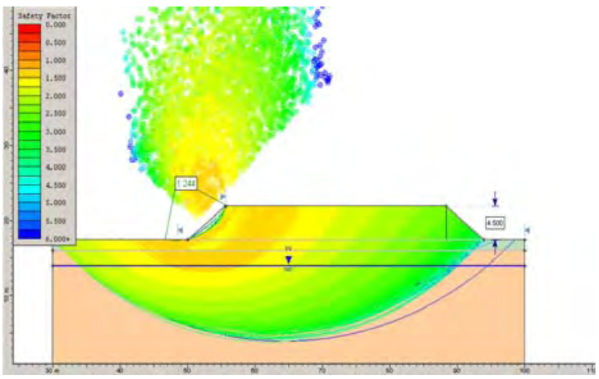
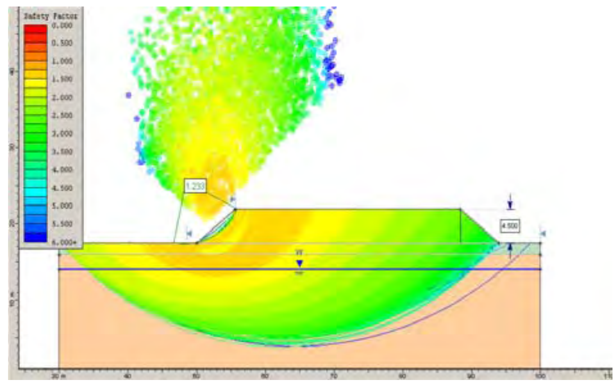


Figure 4: Profile of iron ore stack

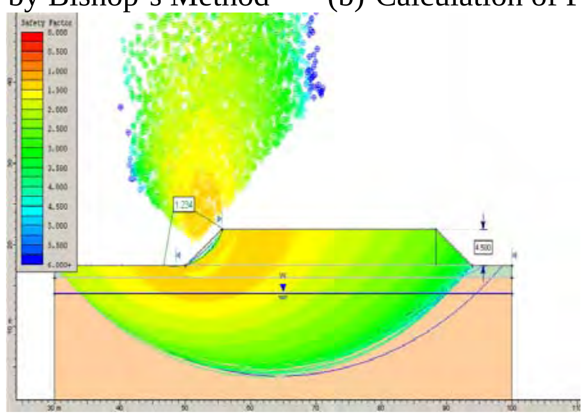
Three stacks of 44 m wide are modeled with 20m spaces in between the stack for the model used for the analysis in the software. The factor of safety was obtained by three different methods namely Bishops's method, Spencer's method and Mongersten-price's method (see Ranjan and Rao, 2000). Figure 5 shows the factor of safety (FOS) obtained by all three methods. Factor of safety by all three methods during various stages of constructions are summarized in Table 2. It was observed that constructing the Iron ore in three stages, as 4.5m, 1.5m and 1.5m is stable. Hence, the same construction sequence was proposed.



(a) Calculation of FOS by Bishop's Method



(b) Calculation of FOS by Bishop's Method



(C) Morgenstern Price – Circular slip surfaces

Figure 5: Factor of Safety obtained by different methods for Iron stacks for stage I

Table 2: Comparison of factor of safety values obtained by various methods for different stages of iron stack

		Factor of safety		
Stage	Height (m)	Bishop's method	Spencer's method	Morgenstern Price's circular slip surfaces
I	4.5	1.244	1.233	1.234
II	6.0	1.220	1.214	1.195
III	7.5	1.158	1.149	1.130

SETTLEMENT ANALYSIS OF IRON ORE STACK

The settlement was calculated by using the software SETTLE 3D. The value of settlement obtained after performing settlement analysis is 4.93m. The load distribution has been considered as 2:1. Because, when strata appears in profile, it may be of interest to consider the effect of a applied load at the surface of the profile on one or more of underlying strata. In such cases, it is often useful to approximate the distributing effect by assuming that the total load on the surface is distributed over an area of the same shape as the loaded area on the surface, but with dimensions which increase by an amount equal to the depth below the surface, that is according to 2 vertical to 1 horizontal method of spread (Ranjan and Rao, 2000). Based on the above settlement value, the time required for 90% consolidation has been calculated. As the site is underlain by sand, assuming double drainage, the time for 90% consolidation was found to be 31.11 years. As, this waiting period is much higher than practical considerations, the installation of prefabricated Vertical Drain (PVD) was supposed to be the best suitable option. Table 3 shows the time stage scenario assumed for the installation of PVD. Figure 6 shows the distribution of consolidation settlement for iron stack at various stages.

Table 3: Time stage scenario considered for iron stack

Time in month	Stage description
0	Stage 1 PVD installation
1	Fill area upto 11.8 m
4	Allowance for settlement under fill
6.5	Stage 1 Iron Ore filling (4.5m)
9	Stage 2 Iron Ore filling (3 m)
11.5	Stage 3 Iron Ore filling (2.5 m)
17	3 month after ore filling
23	6 month after ore filling
26	1 year after ore filling
74	5 years after ore filling

PREFABRICATED VERTICAL DRAINS (PVD)

Based on the data and calculation it was suggested that on installation of PVDs, 90% degree of consolidation would be achieved if the band drain spacing of 1.5m (100mm X 5mm) size was installed up to soft clay layer within the 2.5 month waiting period time. Hence, to reduce the consolidation time the PVDs were suggested to be installed.

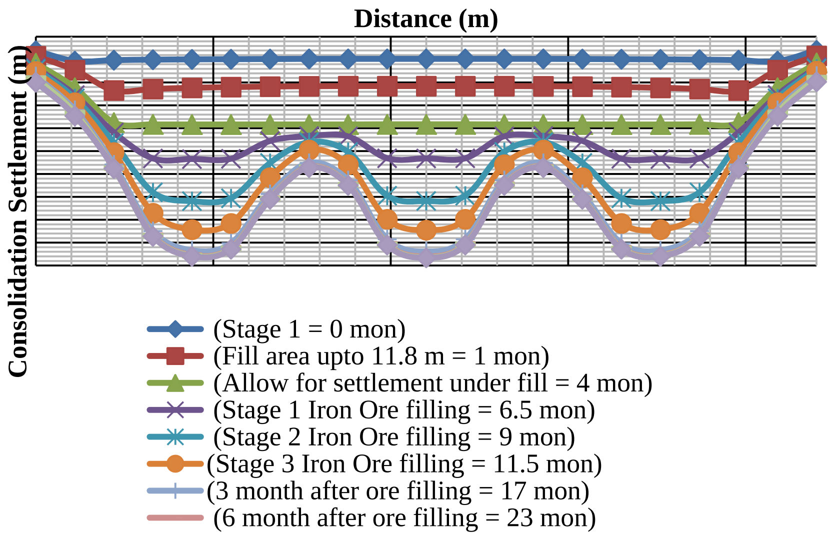


Figure 6: Distribution of consolidation settlement for iron stack

STABILITY ANALYSIS OF COAL STACK

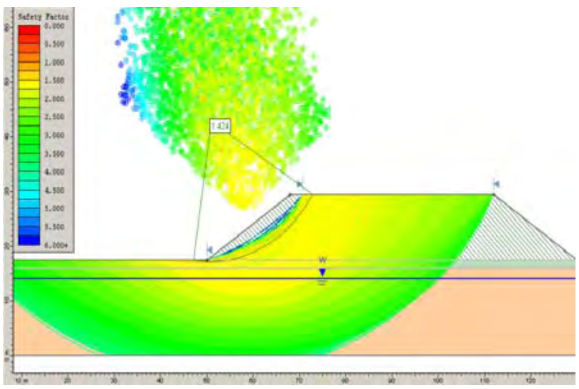
The coal stacking has been assumed to be done with the coal unit weight of 8 kN/m^3. For the Coal stacks, also the Factor of Safety has been determined by three different methods viz. Bishop's method, Spencer method and Morgenstern-Price method. Table 4 explains properties of material assumed. The strength model considered was Mohr- Coulomb failure envelope. Also, the sensitivity analysis was carried out for the parameters like unit weight and angle of internal friction (ϕ).

The coal stacks were analyzed by above mentioned three methods by considering circular failure surface. The factor of safety obtained by Morgenstern Price – Circular slip surface was the critical. Figure 7 shows the typical failure surfaces by the three methods (Bishop's Method, Spencer's Method and Morgenstern Price's method) for Coal stacks by considering circular failure surfaces. It can be seen from Figure 7 that the Spencer's method is giving the critical factor of safety as compared to Bishop's method and Morgenstern Price's method. Table 5 summarizes the Factor of safety obtained by different methods. Figure 8 shows the estimation of factor of safety by considering non-circular failure surfaces by all three methods. Bishop's method is giving the critical factor of safety (FOS = 1.424) for circular failure surfaces while for non-circular failure surfaces it gives factor of safety of 1.268.

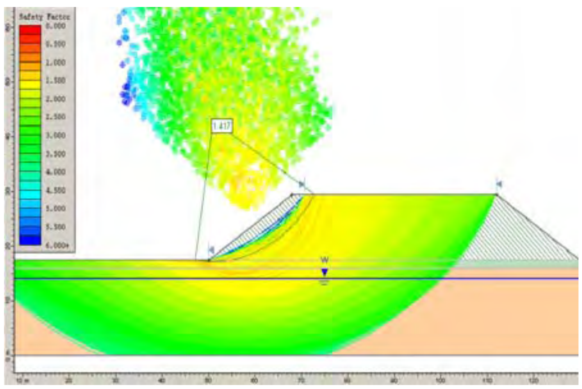
Also, the coal stacks were analyzed by considering the non-circular failure surfaces by the same three methods as mentioned before. Figure 8 shows Factor of Safety obtained by considering non-circular failure surfaces. Table 6 summarizes the factor of safety obtained by different methods.

Table 4: Strength and model properties considered for coal stack

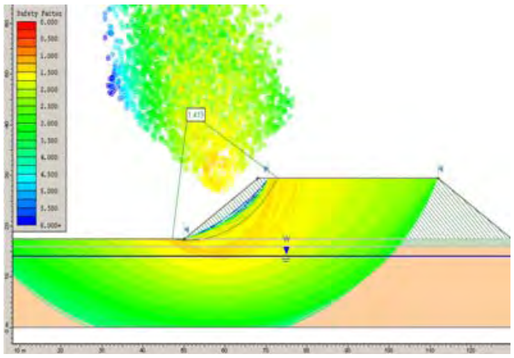
Layer	Unit wt. (kN/m^3)	Strength model	C or C_u (kPa)	ϕ (degree)	Sensitivity carried out for the parameters
Coal	8	Mohr-Coulomb	0	34	Unit wt. = 8 to 10 kN/m^3 ϕ = 30^0 to 34^0
Earth Fill (+7.4 to +9)	18	Mohr-Coulomb	0	30	
Marine clay	17	Un-drained	17 on top (=7.4 level) and then increasing with depth at the rate 3.9kPa /m	0	



(a) Calculation of FOS by Bishop's Method

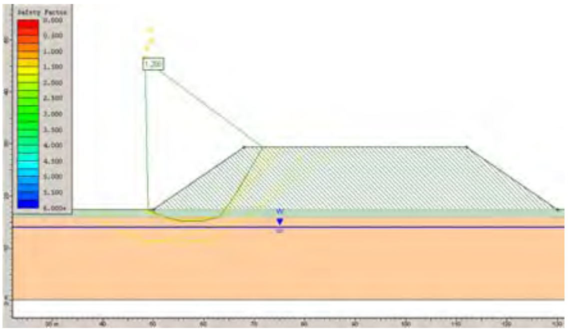


(b) Calculation of FOS by Spencer's Method

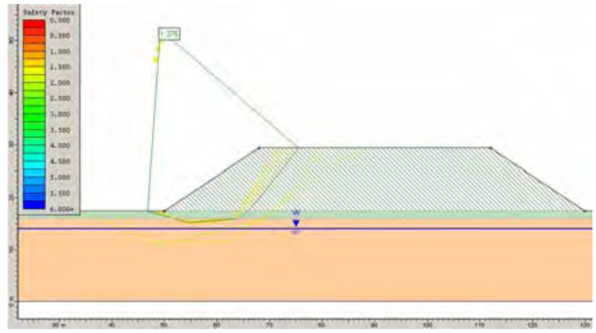


(c) Calculation of FOS by Morgenstern Price's method

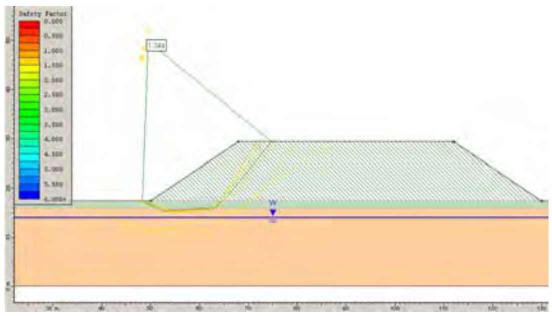
Figure 7: Factor of Safety by different methods for coal stacks by considering circular failure surface



(a) Calculation of FOS by Bishop's Method



(b) Calculation of FOS by Spencer's Method



(c) Calculation of FOS by Morgenstern Price method

Figure 8: Factor of Safety by different methods for coal stacks by considering non-circular failure surface

Table 5: FOS obtained by different methods for circular failure surfaces for coal stack

		Factor of safety			Remark
Stage	Height (m)	Bishop's method	Spencer's method	Morgenstern Price's circular slip surfaces	IS 15284- Part II (2004)
I	4.5	1.424	1.417	1.419	> 1.25

Table 6: FOS obtained by different methods for non-circular failure surfaces for coal stack

		Factor of safety			Remark
Stage	Height (m)	Bishop's method	Spencer's method	*M–P's circular slip surfaces	IS 15284- Part II (2004)
I	4.5	1.268	1.375	1.344	> 1.25

*Morgenstern Price

The factor of safety values was found to be within the allowable limit (1.25) as the unit weight of coal was 8 kN/m^3. With this assumption of unit weight value of coal, the coal stack could be filled with 12m height in one go. But it was observed that if unit weight is marginally increased to 10 kN/m^3, the factor of safety is 1.125 which was not within the allowable limit. Hence, to maintain safety, a two stage process of coal stacking with height say around 8m and then 4m may be a viable solution. This indicated the sensitivity of FOS with unit weight of coal.

SETTLEMENT ANALYSIS OF COAL STACK

The settlement calculated by using SETTLE 3D was 3.95m, assuming the pressure distribution as 2:1 as explained by Ranjan and Rao (2000). Figure 9 shows the plot for distance versus consolidation settlement.

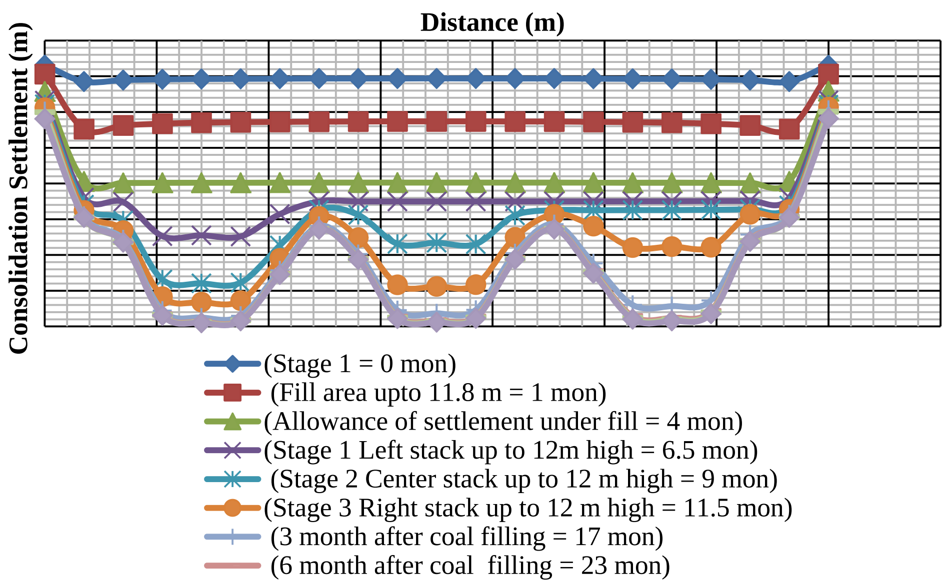


Figure 9: Settlement estimation under the coal stack

INSTALLATION OF PVD

The time required for 90% consolidation was observed to be 31.11 years. This period is very much higher than practical considerations. Hence, the installation of PVDs was considered to be a viable option to accelerate the consolidation process. Calculation showed that the time for 90% could be reduced to 2.5 months by installing PVDs.

STABILITY ANALYSIS OF RAILWAY EMBANKMENT

For the analysis of the railway embankment it was primarily assumed that it can be constructed in four layers. The layers decided were 2.2m+1.5m+1.5m+1m in stages. The factor of safety was determined by three different methods as was done for Iron ore and Coal stacks. Table 7 shows the strength model and properties considered for the stability analysis.

Table 7: Strength model and properties considered

Layer	Unit wt (kN/m^3)	Strength model	C or C_u (kPa)	ϕ (phi) (degree)
Earth Fill	18	Mohr Coulomb	0	30
Marine clay	17	Undrained	10 on top (=7.4 level) and then increasing with depth at the rate 3.9kPa /m	0

Figure 10 shows the variation of total settlements in the model considered for the Railway embankment. Railway embankment is modelled in three staged construction (43.8 m wide; 2:1 slope). Figure 11 shows the factor of safety by all three methods viz. Bishop's method, Spencer's method Morgenstern Price method by considering circular slip surface. Factor of safety is investigated immediately after the placing the embankment fills (No consolidation/strength gain considered due to coal fill). It can be seen that Spencer's method has given critical factor of safety for first 3 stages while for fourth one Morgenstern-Price method is giving critical factor of safety. Since, all these critical factor of safety are more than 1.25, the suggested stages of construction are safe. Table 8 shows factor of safety calculated all three methods for various stages of construction.

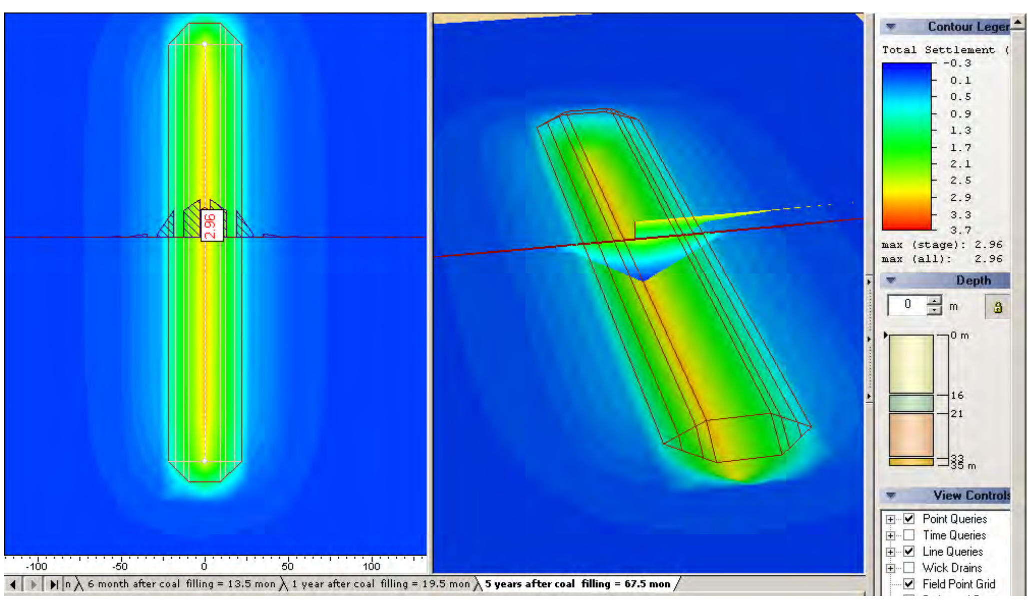
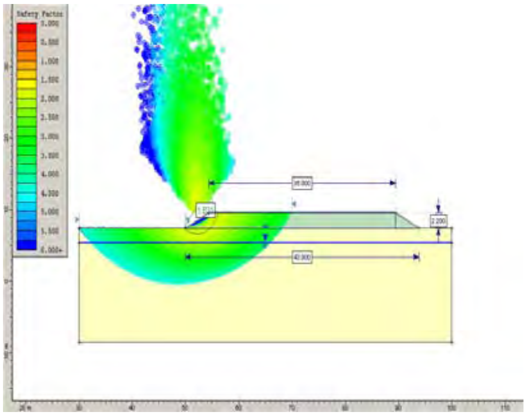
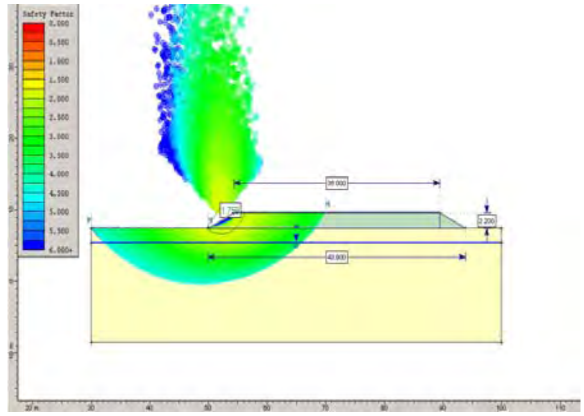


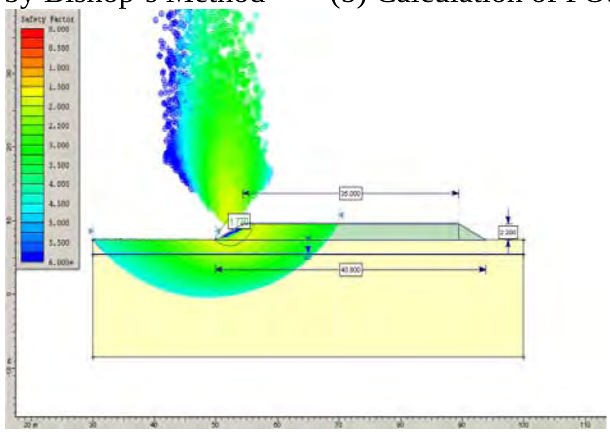
Figure 10: Variation of total settlements in railway embankment



(a) Calculation of FOS by Bishop's Method



(b) Calculation of FOS by Spencer's Method



(c) Morgenstern Price – Circular slip surfaces

Figure 11: Factor of safety by different methods for railway embankment

Table 8: Factor of Safety values calculated by different methods for various stages of construction of railway embankment

		Factor of safety			Remark
Stage	Height (m)	Bishop's method	Spencer's method	*M–P's circular slip surfaces	IS 15284- Part II – 2004
I	2.2	1.821	1.759	1.770	> 1.25
II	3.7	1.367	1.331	1.337	
III	5.2	1.279	1.223	1.279	
IV	6.4	1.224	1.175	1.181	

SETTLEMENT ANALYSIS OF RAILWAY EMBANKMENT

Railway embankment is modeled in three staged construction (43.8 m wide; 2:1 slope). Maximum consolidation settlement computed using software SETTLE 3D was observed to be

2.84m. It was observed that if 1.5m triangular grid spacing PVDs are provided, the time for 90% consolidation will be 6 months. Hence, 1.5m triangular gird spacing has been proposed.

Table 9 shows the time versus load scenario considered for railway embankment analysis. Figure 12 shows distance versus settlement profile for railway embankment.

Table 9: Time stage scenario considered for railway embankment

Time in month	Stage description
0	Stage 1 PVD installation
2.5	Embankment height up to 2.2m
5	Embankment height up to 4.7 m
7.5	Embankment height up to 6.2 m
10	2.5 month embankment upto 6.2 m
13.5	6 month after full filling but embankment up to 2.2m removed at this stage
19.5	1 year after removal
67.5	5 years after removal

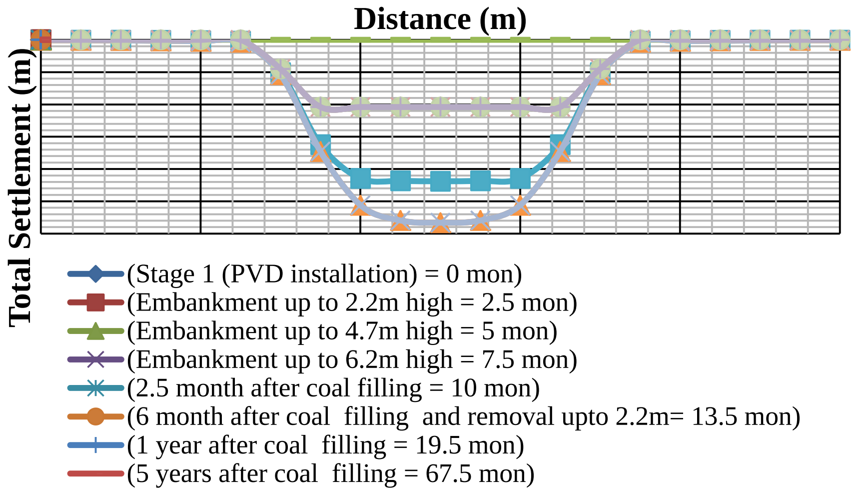


Figure 12: Distance versus settlement for railway embankment

CONCLUSIONS

For proposed bulk terminal in Beira, Mozambique with in-situ soft soil conditions, stability analysis with ground improvement techniques using local soil conditions are proposed in the present case-study effectively. Man-made slope stability analysis for iron ore stack, coal stack and railway embankments have been analyzed by using three major different methods of stability analysis adopting limit equilibrium method. The settlements have been calculated by using software SETTLE 3D. The construction of iron stack was proposed in three stages of heights 4.5m, 1.5m and then 1.5 m after rigorous numerical analysis. Coal being a lighter material than iron, the coal stack is proposed to be constructed in one stage only. Railway embankment construction is proposed in four stages with heights as 2.2m, 1.5m, 1.5m and then 1.0m. It was observed that the period for 90% settlement was very high from practical considerations for all three types of stacks. Hence, PVDs were proposed in the field to accelerate the settlement and to reduce the time for 90% settlement for all three types of stacks viz. iron ore stack, coal stack and railway embankment. The slope stabilities of all the three types of stacks are ensured by maintaining factor of safety more than unity.

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