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SETTLEMENT, SLOPE STABILITY AND SEEPAGE ANALYSES BY NUMERICAL MODELLING METHOD AND THEIR APPLICATIONS IN PRACTICE

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Abstract
The encountered situations during the design process of a gully erosion control site in Kano State are discussed in this article. The project was to design a rectangular concrete lined drainage channel with short side walls to efficiently convey flood water and prevent embankment erosion. Because of the embankment depth and soil type on the site which are mostly silty/clayey sand, settlement of the huge concrete channel, seepage and the unprotected embankment slope were issues of major concern. Settlement, slope stability and seepage analyses and designs were some of the several activities undertaken for the project. The anticipated total settlement prediction was performed by numerical simulation from which the differential settlement was then calculated. The prediction of the safety factor to determine the stability of the slope was performed by numerical simulation using SLOPE/W. The hydraulic velocity and rate of seepage prediction was performed by numerical modelling using SEEP/W. The use of numerical technique was specifically recommended by the consultants of the funder of the project, the World Bank. It was observed that numerical modelling technique provided accurate results of settlement, factor of safety, hydraulic velocity and rate of seepage and was therefore recommended for both research and practical applications.

1.0 INTRODUCTION
It is a common understanding that the responsibility of a civil engineer is to develop reliable, safe and effective systems for the society by mitigating risk and avoiding failure. These responsibilities includes forecasting, predictions and prevention against catastrophes due to human activities and natural hazards. Natural hazards, when occurred, cause enormous damage on human life and economic loss. In all engineering systems, cost effectiveness must also be put into considerations. Prediction of the anticipated total and differential settlement of shallow foundations in cohesive and cohesionless soils is prone to several uncertainties such as variations in soil properties with lateral and axial distances, perfection in the laboratory experimental results, etc. Numerous methods have been developed to predict the settlement of shallow foundations in soils. With advancement in technology and development of sophisticated numerical methods such as finite element method, the consideration of the constitutive behavior of soils has become a subject of wide discussion [1]. The constitutive behavior governs the response of soil under the footing and therefore majorly determines the value of bearing capacity and settlement [2 - 3].

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Numerical modelling is a powerful simulation and mathematical tool that makes it possible to solve complex engineering problems. In a study on the constitutive behaviour of soils, Salahudeen and Sadeeq [4] observed that soils can be successfully modelled with numerical analyses using some basic soil properties as input data. It was also discovered that it is realistic to idealize the material behaviour of the soil, which is non-linear with plastic deformations and stress-path dependent, in a more realistic approach [5]. The slope stability and seepage analyses in geotechnical engineering have followed nearly the developments in soil and rock mechanics. Slopes are either engineered or occur naturally. To minimize these enormous damages, especially those caused by geohazards, an appropriate preventing techniques are needed and reliability analysis relating geohazards should be adopted [6].

To quantitatively assess the stability of a slope in an engineered or naturally occurring slope stability failure mechanisms analysis, a parameter known as factor of safety (F) is used which is simply the ratio of the resistance forces to the gravity forces parallel to the slope. A value of F greater than 1 indicates stability, whereas F less than 1 implies instability. F value of 1.5 is generally reported to be satisfactory in the literatures [7]. Thus, the transition between stability to collapse may be envisaged computationally as a decrease in the factor of safety to values below unity. The quantitative determination of the stability of slopes is necessary in a number of engineering activities, such as: (a) the design of earth dams and embankments, (b) the analysis of stability of natural slopes, (c) analysis of the stability of excavated slopes, (d) analysis of deep-seated failure of foundations and retaining walls, (e) open pit mining, (f) road cuts. Conventional forms of slope stability analysis are limited to simplistic problems in the scope of application, encompassing simple slope geometries and basic loading conditions, and as such, provide little insight into slope failure mechanisms [8].

Soil slope stability problems involve complexities relating to geometry, material anisotropy, non-linear behavior, in-situ stress and the presence of several coupled processes (e.g. pore pressure, seismic loading, etc.). To address these problems, numerical simulation methods have been proved to provide more accurate solutions, which is a major limitation in the conventional techniques. Advances in computational methods and the availability of commercial numerical modelling codes means that the simulation of potential soil slope stability failure mechanisms could, and in many cases should, form a standard component of a soil slope investigation [7, 9 - 10]. In this study, the slope stability analysis of an earth dam embankment was performed using SLOPE/W in GeoStudio. It is good to note that the reliability of numerical modelling software and their limitations with respect to field application largely depend on the expertise of the modeler.

Flood channels, just like earth dams have always been associated with seepage as they impound water in them. The water seeks paths of least resistance through the embankment. Seepage will become a bigger problem if it carries materials along with it. Seepage must be controlled to prevent the erosion of embankment or its foundation. Different methods like analytical, electrical analogy and flownet have been used to study and monitor seepage in dams and embankments [11]. In this study, the seepage analysis of the earth dam embankment was performed using SEEP/W in GeoStudio.

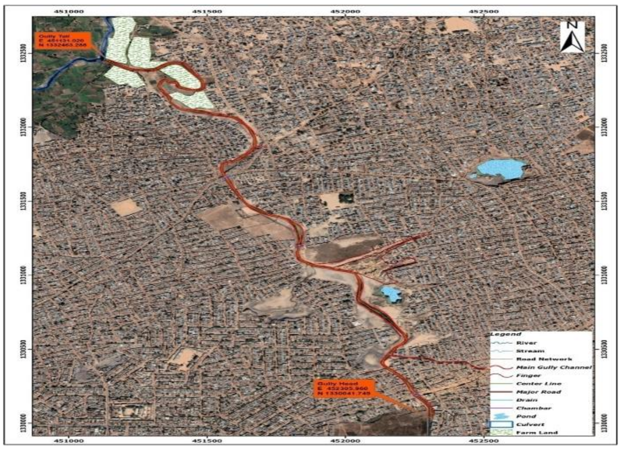

Figure 1: Satellite Imagery of the Site

Some of the important factors causing failure of embankments are slope failures, settlement and seepage through the embankment materials and hence their analysis in embankment dam design is of greater importance. Recently, Finite Element Method (FEM) is being used by geotechnical engineers analysis of geotechnical problems and designs [12 - 16]. Olonade and Agbede [17] performed a computer simulation of the groundwater flow through a porous medium in the Northern region of Nigeria. The results of the simulation was within acceptable limits. The objective of this study is to analyze the settlement, slope stability and seepage potential of a concrete lined flood channel with erosion problem and its embankment in order to ensure both safety and sustained economic development of the community. These analyses of the design parameters are very vital for the safety, stability and economic or optimal design of the flood channel to mitigate the flood and erosion problems.

2.0 MATERIAL AND METHODS

2.1 Material

The geotechnical investigation works for the site (located at Latitude 1330041.749N and Longitude 452305.960E of the gully head and 1332463.288N and 451131.020E of the gully tail) involves seven (7Nos) boreholes to depths of 10.0m (BH1 and 2) and 5.0m (BH3 - 7) and 9 Nos trial pitting to depth of 3.0m explored to characterize the subsoil for the purpose of settlement, slope stability and seepage analyses and design. The site is located at Bulbula, Kano State, Nigeria (see Figure 1 for the site map and Figure 2 for pictures).

Figure 2: Site Photographs

The test borings were drilled using the rotary drilling machine. In each test bore, Standard Penetration Tests (SPT) was conducted at 1.5m interval where samples were also taken. The sampling procedure consisted of driving a standard split spoon as set forth in ASTMD1586-1990 and BS 5930. The laboratory tests were conducted in accordance with the relevant British Standard as Specified in BS 1377 [18]. This was by repeated blows of hammer of 63.5kg weight falling through 760mm height. Average values of the parameters used for modelling the soil and the foundation element are presented in Table 1. Values of Young's modulus and Poisson's ration were obtained fron set of tables presented by Das [19].

Table 1: Average parameters for modelling and general computations

Parameter	Unit	Soil	Concrete
Bulk unit weight	kN/m^3	18.0	24
Dry unit weight	kN/m^3	17.3	--
Friction angle	Degree	24	--
Dilatancy angle	Degree	0.0	--
Cohesion	kN/m^2	10	--
Permeability	m/sec	1.2×10^{-5}	--
Young's modulus	kN/m^2	10200	2.74×10^{7}
Poisson's ratio	--	3.324	0.2
Soil model	--	Mohr-Coulomb	
Material behavior	--	--	Linear (Isotropic)

2.2 Methods

2.2.1 Laboratory experimental procedure

The results presented in Table 1 and 2 were obtained through the following experimental procedures. The laboratory tests were performed to determine the index and strength properties of the soil in accordance with BS 1377 [18]. The experimental tests conducted include sieve analysis, consistency limits, density, permeability, specific gravity and direct shear test for strength. The strength test was conducted using the direct shear method. The permeability test was conducted using laboratory constant head hydraulic conductivity procedure. The specific standards used in conduction the tests presented in Table 2 has been detailed in the last column of the table.

2.2.2 Settlement modelling

Total settlement

The total settlement prediction was done using PLAXIS software package. Prediction of maximum total anticipated settlement of the channel structure was done on the lined rectangular channel with concrete at different chainages along the gullies based on structural applied loads at embedment depth of 0.6 m. A maximum applied foundation pressure of 40 kN/m^2 was used and point loads of 20 kN representing each side wall of the rectangular channel. Plaxis 2D (plane strain model) is a finite element package used for two-dimensional analysis of deformation and stability analysis in geotechnical engineering. It uses advanced soil constitutive models for the simulation of the non-linear, time dependent and anisotropic behaviour of soils. Plaxis portfolio models the structure, the soil and the interaction between the structure and the soil. Soil layers and foundation structure parameters are inputted into Plaxis and the construction stages, loads and boundary conditions are defined in an already defined geometry cross-section containing the soil model. Plaxis then automatically generates the unstructured 2D finite element meshes with options of global and local mesh refinements. Using its calculation facilities, Plaxis undergoes a calculation process and presents the calculation and model outputs which can be accessed in animation and/or numerical forms. The input parameters used in modelling the embankment are the derived soil parameters from both the SPT and laboratory results which include the cohesion, friction angle, dilatancy angle, modulus of elasticity, Poisson's ratio, hydraulic conductivity, bulk and dry unit weights and plasticity index. Further details can be found in Plaxis 2018 Version manual [20].

Differential settlement analysis

The differential settlement was computed using the angular distortion approach based on the total settlement computed by the numerical modelling method.

$$\Delta S = S_T / l \quad (1)$$

Where ΔS = Differential Settlement, S_T = Total Settlement and l = distance between the two points under consideration.

Slope stability modelling

The SLOPE/W package for slope stability simulations in GeoStudio was used for modelling the slope stability of the gully site embankment. SLOPE/W is a two-dimensional axisymmetric finite element software product that can be used to perform stress, and stability analyses of embankments. Its comprehensive formulation makes it possible to analyse both simple and highly complex problems like a simple linear elastic deformation analysis or a highly sophisticated nonlinear elastic-plastic effective stress analysis. In SLOPE/W, finite elements numerical modelling methods translate a set of differential equations into matrix equations for each element, relating forces at nodes to displacements at nodes. Further details can be found in GeoStudio 2020 Version manual [21].

Geo-Studio software portfolio includes simulation of soil and soil-structure interaction. Geo-Studio is an axisymmetric finite element package used for two-dimensional analysis of deformation and stability in geotechnical engineering. It uses advanced soil constitutive models for the simulation of the non-linear, time dependent and anisotropic behaviour of soils. Geo-Studio portfolio models the structure, the soil and the interaction between the structure and the soil. Soil layers parameters are inputted into Geo-Studio and the construction stages, loads and boundary conditions are defined in an already defined geometry cross-section containing the soil model. Geo-Studio then automatically generates the unstructured 2D finite element meshes with options of global and local mesh refinements. Using its calculation facilities, Geo-Studio undergoes a calculation process and presents the calculation and model outputs which can be accessed in animation and/or numerical forms. The input parameters used in modelling the embankment are the derived soil parameters from the laboratory results which include the cohesion, friction angle, bulk and dry unit weights.

Seepage modelling

The seepage analysis in this project was performed to determine the seepage loss and the hydraulic conductivity of the soil which is necessary for estimating the quantity of underground seepage under various hydraulic conditions and for making stability analyses of river slopes as they are subject to seepage forces. When water channels convey flood water, there will be penetration of water into the earth embankment and therefore analysis of the seepage hydraulic velocity and flux is inevitable. The seepage analysis was performed at different locations along the gully. The selected sections of the gully for which analysis was performed are those locations with concerned features based on soil properties, slope height, channel width and location. Seepage simulations was performed using SEEP/W in Geo-Studio package. The working system of Geo-Studio has been described in slope stability modelling subsection. The input parameter used in modelling the flow in embankment is majorly the hydraulic conductivity of the soil obtained from laboratory constant head hydraulic conductivity test and presented in Table 1.

3.0 RESULTS AND DISCUSSIONS

3.1 Average Geotechnical Properties of the Site

The Stratigraphy of the subsurface deposits as observed from the logs of test bores performed at this site exhibited slight variations in strata from one location to the other, but there are some similarities in nature and in strength characteristics of soil strata encountered. The subsoil formation at the boring locations consists of silty sand, clayey sand, clayey sandy silt, sandy silty clay, laterite and weathered rock. The results in Table 2 show range of values of soil properties from the laboratory test results on samples from the test borings. Figure 3 shows the average particle size distribution.

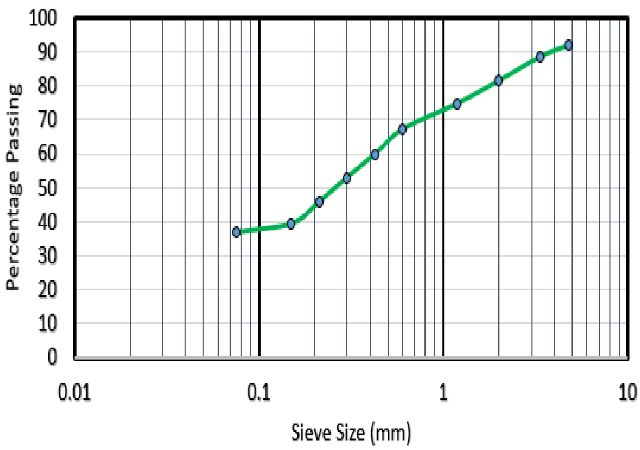

Figure 3: Average particle size distribution of the site soil

Table 2: Range of values of laboratory test results

Soil Property	Minimum	Maximum	Standard
Natural Moisture Content(%)	7	20	BS 1377 (1990) – Part 2
Liquid Limit (%)	21	32	BS 1377 (1990) – Part 2
Plastic Limit (%)	NP	15	BS 1377 (1990) – Part 2
Plasticity Index (%)	NP	17	BS 1377 (1990) – Part 2
Passing # 200 Sieve (%)	2.65	75.23	BS 1377 (1990) – Part 2
Bulk density (kN/m^3)	15.50	19.0	BS 1377 (1990) – Part 2
Permeability (m/sec)	2.95×10^{-7}	1.29×10^{-3}	BS 1377 (1990) – Part 5
Specific Gravity	2.60	2.64	BS 1377 (1990) – Part 2
Apparent Cohesion (kN/m^2)	0	3	BS 1377 (1990) – Part 8
Angle of Internal Friction (Ø)	22	36	BS 1377 (1990) – Part 8

3.2 Settlement

The results of settlement analyses are presented in Table 3 while samples of the model plates used for numerical simulations are presented in Figures 4 and 5. Conventionally, the allowable settlement value of 25 mm is generally recommended for sensitive engineering structures like buildings as stipulated by the European Committee for Standardization otherwise known as Eurocode 7. However, this allowable value is 50 mm for structures founded on sands [22 - 23]. Eurocode 7 [24] recommended limiting values for maximum acceptable foundation settlement as: limiting values for total settlement of 25 mm for isolated shallow foundation and 50 mm for raft foundation. Since the bottom slab of the concrete channel is designed as raft footing, which spread the loads over a wise area, the limiting value of 50 mm for raft foundation was considered for this project. Eurocode 1 [25] recommended a maximum allowable differential settlement and angular distortion of 20mm and 0.00333 respectively for serviceability limit state in rafts founded on sand. The observed settlement and differential settlement values in this project are mostly within the acceptable limits. However, there are locations in which the limiting conditions were not met. Therefore, mechanical predensification and/or special treatments (mixing with coarse grain materials) [26-29] of the soils is recommended at these locations using soil compaction machines to reduce the compressibility of the soil before placing the concrete channel's foundation. This settlement problem is an issue of major concern at Chainages 1+000 - 1+600 and 2+200 - 3+000 as obvious from Table 3. The use of rectangular concrete channel has the advantage of wide spread of load over a large area thereby mobilizing a larger soil surface for bearing the load and thereby minimizing the anticipated settlement.

Table 3: Results of total settlement and differential settlement

Test Point Vicinity	Total Settlement (mm)	Differential Settlement (mm)	Angular Distortion	Deflection Ratio	Remark
0+000	12.25	9.41	0.00004705	0.000032935	Satisfactory
0+200	25.87	13.62	0.0000681	0.00004767	Satisfactory
0+400	10.1	15.77	0.00007885	0.000055195	Satisfactory
0+600	17.39	7.29	0.00003645	0.000025515	Satisfactory
0+800	14.51	2.88	0.0000144	0.00001008	Satisfactory
1+000	67.21	52.7	0.0002635	0.00018445	Not Satisfactory
1+200	14.91	52.3	0.0002615	0.00018305	Not Satisfactory
1+400	100	85.09	0.00042545	0.000297815	Not Satisfactory
1+600	8.55	91.45	0.00045725	0.000320075	Not Satisfactory
1+800	21.56	13.01	0.00006505	0.000045535	Satisfactory
2+000	14.43	7.13	0.00003565	0.000024955	Satisfactory
2+200	84.88	70.45	0.00035225	0.000246575	Not Satisfactory
2+400	14.41	70.47	0.00035235	0.000246645	Not Satisfactory
2+600	80.72	66.31	0.00033155	0.000232085	Not Satisfactory
2+800	86.6	5.88	0.0000294	0.00002058	Not Satisfactory
3+000	29.08	57.52	0.0002876	0.00020132	Not Satisfactory
3+200	14.51	14.57	0.00007285	0.000050995	Satisfactory
3+400	33.21	18.7	0.0000935	0.00006545	Satisfactory

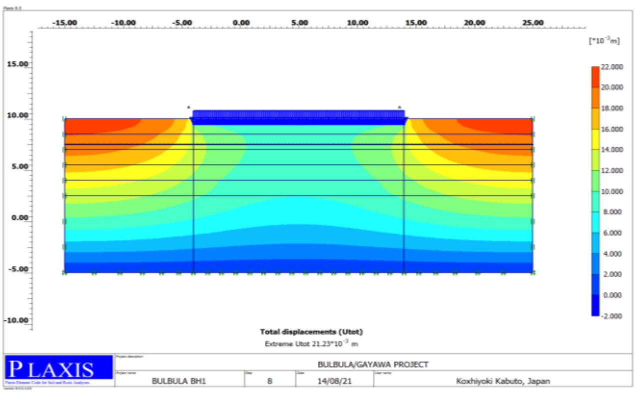

Figure 4: Model of settlement analysis around chainage 0+300

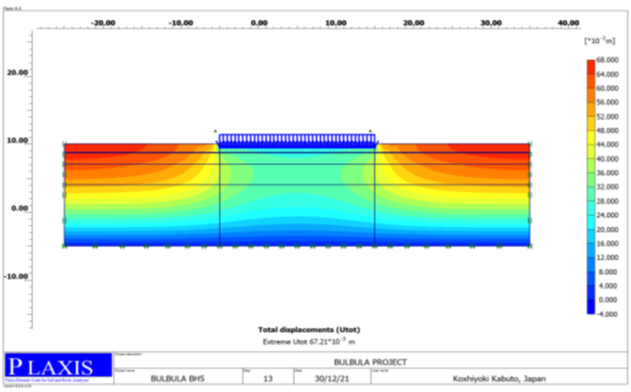

Figure 5: Model of settlement analysis around chainage 1+000

3.3 Slope Stability

Slope stability analysis was performed based on average soil properties within the vicinity of trial pits/boreholes as obtained from the nearest trial pit/borehole. The soil properties of all soil layers encountered during excavation for representative soil samples were considered during the analysis. However, output results are presented for the most critical locations encountered. The analysis was performed for areas with the most observable issues of stability concerns around the vicinity of locations where soil investigation was conducted. The slope stability results for this project are all satisfactory. When an embankment has a factor of safety value of 1.0, it implies that equilibrium is just attained and any value below 1.0 is an indication of certainty of failure. Safety factor value above 1 is an indication of safety but a minimum of 1.5 factor of safety value is conventionally recommended. None of the simulations has safety factor less than the minimum value of 1.5. Detailed results of the slope stability analysis with their corresponding slope heights are presented in Table 4.

The factors of safety first estimated in the unlined channel are very low and seriously below the minimum requirement of 1.5 and therefore not satisfactory and lining the channel with concrete was strictly recommended. However, the concrete lined channels, whichever of rectangular or trapezoidal is favored considering other design criterial is hereby recommended for adequate and efficient solution to the gully problem. To enhance more stability of the slopes, it is recommended that steep slopes be stabilized mechanically by ensuring a gentle slope of the embankments [12, 29]. In the construction of the engineered embankments, a minimum slope of 1:1 (or gentler) should be considered [5, 26] throughout and in cases where this slope cannot be achieved for reasons to be determined by the site engineer, gabion mesh is recommended to compensate the slope for stability. Some of the model plates used for the numerical modelling are presented in Figures 6 and 7.

Table 4: Results of factor of safety for slope stability analysis

Test Point Vicinity	Embankment Height (m)	Factory of Safety	Remark
Around TP1	3.0	3.51	Satisfactory
Around TP2	4.5	4.08	Satisfactory
Around TP3	4.0	5.12	Satisfactory
Around TP4	2.0	3.92	Satisfactory
Around TP5	2.5	4.52	Satisfactory
Around TP6	4.0	5.10	Satisfactory
Around TP7	3.5	5.02	Satisfactory
Around TP8	3.0	5.40	Satisfactory
Around TP9	3.0	5.36	Satisfactory
Around BH1	4.0	3.95	Satisfactory
Around BH2	2.0	4.71	Satisfactory
Around BH3	3.7	2.75	Satisfactory
Around BH4	2.9	3.34	Satisfactory
Around BH5	4.1	3.02	Satisfactory
Around BH6	3.5	2.78	Satisfactory
Around BH7	3.1	4.65	Satisfactory

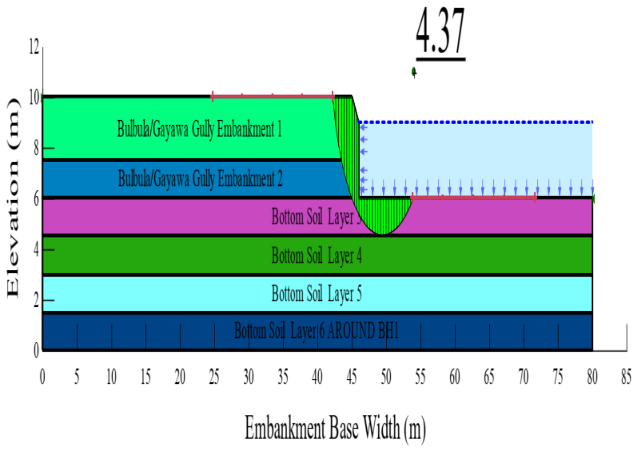

Figure 6: Model 1 of slope stability analysis

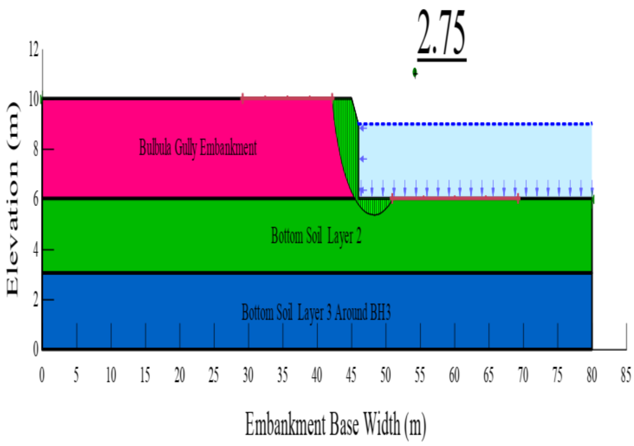

Figure 7: Model 2 of slope stability analysis

3.4 Seepage

Results of seepage analyses show that the maximum hydraulic velocities and flux at most of the sections around the locations of the embankments considered are not satisfactory, thereby necessitating the use of concrete lining. For the construction of embankments, the coefficient of permeability is generally used to qualify the suitability of a particular soil horizon. Dikes and embankments without any impermeable clay core may be built from soils having a coefficient of permeability less than 1 x 10^{-4} m/s. In any case, the coefficient of permeability greater than 1 x 10^{-6} m/s is considered rapid [30]. Also, an average seepage rate of 1.157 x 10^{-4} to 2.315 x 10^{-4} m^3/s is considered acceptable, but corrective measures should be taken to reduce soil permeability when higher values exist. The most serious concerns are for internal erosion or piping within an embankment when the signs of distress are often hidden until severe internal damage has occurred [30].

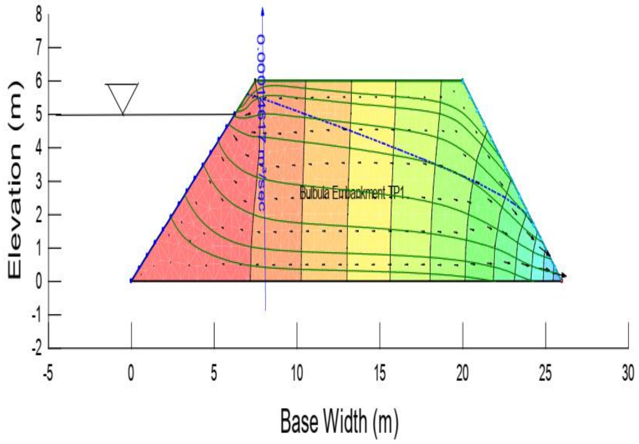

Figure 8: Model of seepage analysis around chainage 0+000

It is reported in the literature that there are two major procedures for quickly alleviating a seepage problem: reduce the hydraulic head and pressure causing the problem (reservoir drawdown) or control the exits of the seepage. For this particular project, controlling the exits of the seepage is the applicable of the two options. Constructing sandbag or other types of ring dikes around sand boils can be used to control the seepage exit. Seepage exits can also be controlled with a weighted filter (e.g. geotextile) constructed by placing a layer of filter material over the seepage exit and overlaying that with pervious drainage material. Meanwhile, providing a concrete channel is a better alternative that provides a permanent solution to the seepage problem which will also aide the slope stability. Summary of the seepage analysis results are presented in Table 5. Based on these results, it is highly recommended that the gully channel be lined with concrete due to the highly permeable soil type which is highly susceptible to collapse and erosion.

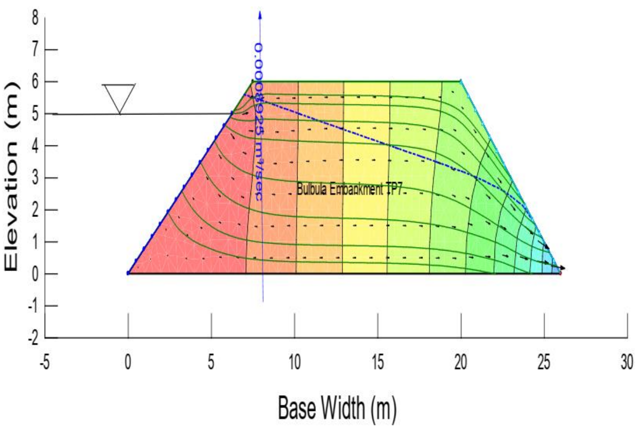

Figure 9: Model of seepage analysis around chainage 3+500

Table 5: Results of maximum hydraulic velocities and flux

Test Point Vicinity	Max. Hydraulic Velocity (m/s)	Max. Hydraulic Flux (m^3/s)	Remark
Around TP1	1.266×10^{-4}	1.462×10^{-4}	Satisfactory
Around TP2	4.576×10^{-3}	7.350×10^{-3}	Not Satisfactory
Around TP3	2.532×10^{-3}	4.100×10^{-3}	Not Satisfactory
Around TP4	5.614×10^{-4}	4.151×10^{-4}	Not Satisfactory
Around TP5	2.341×10^{-6}	1.630×10^{-6}	Satisfactory
Around TP6	4.001×10^{-4}	6.040×10^{-4}	Not Satisfactory
Around TP7	7.455×10^{-4}	8.925×10^{-4}	Not Satisfactory
Around TP8	5.514×10^{-3}	6.254×10^{-3}	Not Satisfactory
Around TP9	3.756×10^{-4}	4.038×10^{-4}	Not Satisfactory
Around BH1	3.043×10^{-5}	4.639×10^{-5}	Satisfactory
Around BH2	5.657×10^{-5}	4.072×10^{-5}	Satisfactory

The hydraulic velocities and flux estimated in the unlined channel are very high and not satisfactory. Therefore, concrete lining is highly recommended for adequate and efficient solution to the gully problem. Some of the model outputs are presented in Figures 8 and 9.

4.0 CONCLUSION

Based on the results and observations of the study, it is concluded that numerical modeling technique of predicting the total settlement of foundations in geotechnical engineering is effective and more accurate than the conventional methods that are based on approximations. It was also concluded that numerical modeling technique of predicting the safety factor of natural or engineered slopes in geotechnical engineering yielded reliable factor of safety results. From the results of hydraulic velocity and rate of seepage obtained in this study, it was obvious that the numerical simulation technique is highly recommended for all geotechnical seepage analysis.

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