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Geotechnical Stability of Satkhira Polder embankment in Bangladesh against Cyclonic Storm Surges

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Abstract : This study aims at finding the geotechnical stability of the Satkhira Polder embankments, which is an exposed coast of Bangladesh. To investigate the geotechnical parameters of the recently improved Polder embankments, SPT test was performed at 3 locations. Soil samples (both undisturbed and representative) were collected to perform direct shear test, tri-axial test, and consolidation test at laboratory. Some model related soil parameters were estimated based on empirical correlations. Later, the Polder embankment was modeled in PLAXIS-3D, a finite element software, based on field condition and soil parameters extracted from soil test results for different combinations of surge depth and thrust force which are generated due to propagation of cyclone induced surge wave. The surge depth and thrust force were computed from simulation results of numerical and analytical models. The embankment model was analyzed for different conditions to determine global factor of safety and settlement condition. The results show that the improved Satkhira Polder embankment is safe against storm surges that the area recently encountered.

***IndexTerms* - Polder, SPT, Tri-axial test, Numerical analysis, PLAXIS-3D.**

1. Introduction

Coastal region of Bangladesh, the most low-lying part of the country, is the homeland of 50 million people, nearly one-third of huge population of densely populated Bangladesh (Marziya 2010-11).The Ganges, the Brahmaputra and the Meghna that constitute one of the largest river systems in the world drain through the coastal region into the Bay of Bengal has made the region more complex and unstable. Additionally, coastal region of Bangladesh is highly susceptible to tropical cyclones and storm surges due to its geographical location. The destruction due to the storm surge flooding is a serious concern along the coastal regions of the countries, for example along the coasts of Bangladesh, India and Myanmar. Bangladesh is on the receiving end of about 40% of the impact of total storm surges in the world (Murty 1992, pp.251-273). The most deadly cyclones of the modern era struck Bangladesh in 1970 and 1991. Cyclone SIDR struck Bangladesh in November 2007, killing over 3,000 people, injuring over 50,000, damaging or destroying over 1.5 million homes, and affecting the livelihoods of over 7 million people (Dasgupta 2009, pp.1).Moreover, the adverse effects of Climate Change – especially High Temperature, Sea-level Rise, Cyclones and Storm Surges, Salinity Intrusion, Heavy Monsoon Downpours etc. has aggravated the miserable conditions of people living here. From 1960 to 1980 a total of 123 coastal polders were constructed to protect low-lying coastal areas from tidal floods and salinity intrusion in southern Bangladesh (Ahmed 2011). The failure of these earth embankments due to cyclone and storm surges makes the scenario more vulnerable which results in more causalities and economical loss.

Lack of proper construction, poor maintenance after a natural calamity, climate change effects making the embankments less effective to withstand the region from strong water and wind thrust and making the inhabitants exposure to the natural calamities. The aim of our study is to investigate the present stability conditions of the embankments around coastal polders. The soil profile and construction technique of the embankments of polders more of less same. We have selected Bhola zone as a prototype for investigation .Finite element (PLAXIS 3D)(Vilas, Moniuddin 2015) modeling of Bhola embankment considering primary soil parameters of earth embankment and sub-soil has been analyzed for investigation of global factor of safety encountering different levels of water level and wind thrust forces.

The most low-lying section of Bangladesh, the coastal region, is home to 50 million people, or roughly one-third of Bangladesh's enormous and densely populated population (Marziya 2010-11). One of the greatest river systems in the world, the Ganges, Brahmaputra, and Meghna, pour through the coastal region into the Bay of Bengal, making the region more complicated and unstable. Moreover, due to its geographical location, the coastal region of Bangladesh is especially vulnerable to tropical cyclones and storm surges. Along the coastlines of the countries, such as Bangladesh, India, and Myanmar, the harm caused by storm surge floods is a significant worry. Bangladesh is affected by around 40% of the overall global storm surge impact (Murty 1992, pp.251-273). In 1970 and 1991, Bangladesh was hit by the two deadliest cyclones of the modern period. In November 2007, Cyclone SIDR slammed Bangladesh, killing more than 3,000 people, wounding more than 50,000, damaging or destroying more than 1.5 million homes, and impacting the livelihoods of more than 7 million people (Dasgupta 2009, pp.1). In addition, the unfavorable effects of climate change, including as high temperatures, sea-level rise, cyclones and storm surges, salinity intrusion, and heavy monsoon rainfall, have exacerbated the wretched living conditions of the local population. In southern Bangladesh, 123 coastal polders were built between 1960 and 1980 to safeguard low-lying coastal villages from tidal flooding and saline intrusion (Ahmed 2011). The failure of these earthen embankments as a result of cyclones and storm surges makes the situation more precarious, resulting in an increase in fatalities and economic loss.

On November 15, 2007, a category IV storm named Cyclone Sidr made landfall in Bangladesh's southwest on the night of, killing 3,406 people and wreaking damage of roughly US$ 1.7 billion (Paul, 2009). On May 25, 2009, Aila made landfall on Bangladesh's southwest coast. 11 coastal regions and more than 3.9 million people were impacted by tidal surges of high to 6.5 meters (UN, 2010). 7,100 people were injured, 1,743 kilometers of embankments were destroyed, and 190 individuals lost their lives as a result of the flooding. Aila also resulted in the deaths of around 150,000 animals, the whole or partial destruction of almost 325,000 acres of cropland, and significant losses to infrastructure (Mallick, 2011).

After cyclones SIDR and AILA struck the coastal zone causing severe damage to the infrastructure, life and property, the Government of Bangladesh (GOB) has taken Coastal Embankment Improvement Project Phase-1 (CEIP–1)(BWDB, 2013).

The First Phase of the Coastal Embankment Improvement Project for Bangladesh aims to: (a) increase the area protected in specific polders from tidal flooding and frequent storm surges, which are expected to get worse due to climate change; (b) increase agricultural production by reducing saline water intrusion in specific polders; and (c) increase the capacity of the Government of Bangladesh to respond quickly and effectively to a crisis or emergency that qualifies.

The objective of this study was to examine the current stability characteristics of the embankments surrounding Satkhira Polder. A finite element, PLAXIS 3D, was used in this study to estimate the factor of safety.

2. Data collection

Satkhira Polder is bordered to the north by Jessore District, on the south by the Bay of Bengal, to the east by Khulna District. The main rivers are the Kopotakhi River across Dorgapur union of Assasuni Upazila, Morichap River, Kholpetua River, Betna River, Raimangal River, Hariabhanga river, Ichamati River, Betrabati River and Kalindi-Jamuna River. Three points was selected for SPT tests in Satkhira Polder. The points have been taken at interval of 0.50 km (500 m). The points are given in Table 1. While performing the tests the cross section of the Satkhira Polder was approximated as Figure 1.

Table 1: Test points at Satkhira Polder

Sl. No.	Test Points	Test Name	Latitude	Longitude
01	Satkhira-01	SPT	22.153650	89.113440
02	Satkhira-02	SPT	22.152140	89.112520
03	Satkhira-03	SPT	22.4750430	88.9984910

During SPT test soil samples were collected to perform Direct Shear test, Tri-axial test, and Consolidation test to find out basic parameters of embankment fill soil and sub-soil. The SPT numbers and geotechnical parameters of the Satkhira Polder at the selected three locations are presented in Table 2. Soil profile and results from laboratory testing shows the soil properties of embankments of Satkhira Polder is more or less same at all locations. The embankment fill soil is Silty Clay which is about 4.5m height. The subsoil is Fine Sand up to 20m from the top of the embankment.

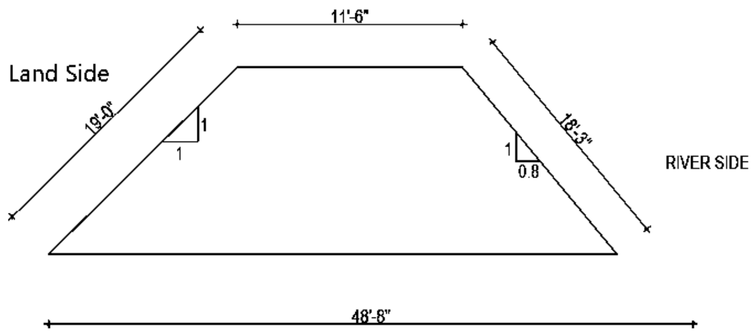

Figure 1: Geometry of the Satkhira Polder

Table 2: Summary of geotechnical parameters of Satkhira Polder

Location	**Depth (m)**	**Soil type**	**SPT N value (Average)**	**Liquid Limit (LL) (ω %)**	**Shear strength parameters from Consolidated Drained Direct Shear test**		**Shear strength parameters from Tri-axial Test**		**Compression Index**	**Swell Index**
					c' kPa	$\varphi'(°)$	c' kPa	$\varphi'(°)$	C_c	C_s
Shaymnagar,Munshigang,Satkhira (BH-01)	0m-13.5m	Silty Clay	2	34			10	24	0.157	0.029
	13.5m-16.5m	Fine Sand	8		8.1	23.9				
Shaymnagar,Munshigang, Satkhira (BH-02)	0m-4.5m	Silty Clay	3				12	25	0.200	0.009
	4.5m-16.5m	Fine Sand	5		6	23.6				
Kaliganj, Satkhira (BH-03)	0m-7.5m	Silty Clay	1				8	20	0.157	0.029
	7.5m-18m	Fine Sand	15		5	30				

2.1 Surge depth and Thrust force for cyclones (Cyclone SIDR, Cyclone 1991)

Storm surges, in addition to claiming human lives, do serious damage to coastal infrastructures. Storm surges are caused by cyclonic winds and the related air pressure reduction. The main contributor is wind, which exerts a stress on the water surface that is proportional to the square of wind velocity. The resulting force exerted on the structures is an important measure in assessing the damage to coastal infrastructure. To estimate the thrust force and surge depth Akter, M. (2016), created an analytical model called Dynamic Force Model (DFM) by using the Variational Iteration Method to calculate the distributive thrust force produced by cyclonic wind and moving surge. They employed the Saint-Venant equations as governing equations, which are effectively 1D shallow water equations derived from the Navier-Stokes equations. The Flow field of DFM was validated by comparing the surge velocity that DFM calculated to the surge velocity that a numerical model, Delft3D.

After validation, the DFM was applied for the coastal zone of Bangladesh to compute thrust forces in the entire coastal zone for the following events: (1) Cyclone SIDR (2) 1991 cyclone (3) Hypothetical SIDR-like cyclone. Table 3 and Table 4 present the effect of Cyclone 1991 and Cyclone SIDR in different locations in coastal regions of Bangladesh.

Table 3: Calculated thrust forces for Cyclone 1991 (after Mahin, 2014)

District	**Thana**	**Cyclone wind speed (km/hr)**	**Surge Depth (m)**	**Thrust Force (kN/m)**	**Surge Velocity (m/s)**
Satkhira	Assasuni	27.64	1.14	0.38	0.31
Satkhira	Debhata	23.43	0.31	0.04	0.10
Satkhira	Kalaroa	20.95	0.00	0.03	0.00
Satkhira	Kaliganj	25.64	0.17	0.39	0.04
Satkhira	Satkhira Sadar	22.72	0.04	0.03	0.03
Satkhira	Shyamnagar	30.76	1.67	1.56	1.09
Satkhira	Tala	25.91	0.04	0.00	0.00

Table 4: Calculated thrust forces for Cyclone SIDR (after Mahin, 2014)

District	Thana	Cyclone wind speed (km/hr)	Surge Depth (m)	Thrust Force (kN/m)	Surge Velocity (m/s)
Satkhira	Assasuni	73.13	1.13	1.39	0.46
Satkhira	Debhata	60.89	0.32	0.36	0.16
Satkhira	Kalaroa	53.88	0.00	0.28	0.00
Satkhira	Kaliganj	66.92	0.15	0.80	0.18
Satkhira	Satkhira Sadar	58.88	0.05	0.38	0.06
Satkhira	Shyamnagar	77.95	1.47	3.32	0.41
Satkhira	Tala	67.55	0.04	0.01	0.01

3. Numerical Modeling Used for Stability Analysis

With the invention of computers, the computation facility has been improved in recent decades which had led to solve repetitive and complex engineering calculations within short time. Utilizing different computer-based geotechnical applications, slope stability assessments are done nowadays. For many years, software using LE formulations has been used. Similarly, interest in finite element (FE) software, which is based on different constitutive soil models, has increased among both scholars and professionals. Nowadays, in geotechnical calculations, both LE and FE-based tools are extensively used. The following sections provide a short introduction to the software utilized in this research, as well as its operating principles. GeoStudio, Slope/W, Slide 2, Slide 3 PLAXIS LE, Geo5 are some of common limit equilibrium software commonly used for slope stability analysis. PLAXIS 2D, PLAXIS 3D, Abacus, RS 2, RS 3, are some common finite element based software used for slope stability analysis.

3.1 PLAXIS software

For the study of deformation, stability, and groundwater flow in geotechnical engineering, the finite element software PLAXIS was created. It is suite a finite element based program used globally for geotechnical engineering and design. The development of PLAXIS was initiated in 1987 at Delft University of Technology. Further the development was initiated to upgrade the software as a comprehensive three-dimensional finite element software that combines a user-friendly interface with comprehensive 3D modeling capabilities. In 2010 PLAXIS 3D was released with capabilities of three dimensional modeling (Brinkgreve, et al., 2016)

3.2 Constitutive Soil Models in PLAXIS

PLAXIS is a geotechnical tool for simulating soil properties. Different soil models and model parameters are used in PLAXIS to quantify the soil properties. There are seven different soil models in PLAXIS. These models include Linear Elastic (LE), Mohr-Coulomb (MC), Hardening Soil (HS), Hardening Soil with Small-Strain Stiffness (HS small), Soft Soil (SS), Soft Soil Creep (SSC), Modified Cam-Clay (MCC), and NGI ADP.

3.3 Mohr Coulomb (MC) model

The MC model combines Hooke's equation of linear isotropic elasticity with the extended Coulomb's failure criteria to create an elastic perfectly-plastic model. The soil is supposed to act as a linear elastic-perfectly plastic material in the Mohr-Coulomb yield surface. Figure 2 and Figure 3 present the fundamental concept of an elastic perfectly plastic model and Table 3 presents the Mohr-Coulomb yield surface in principal stress space.

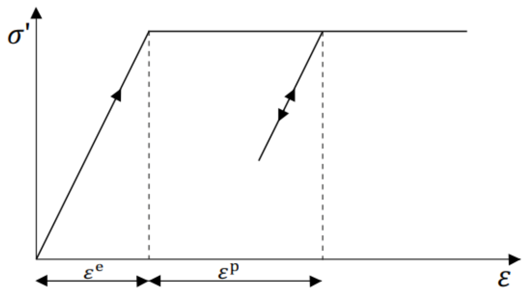

Figure 2: The fundamental concept of an elastic perfectly plastic model (PLAXIS, 2020)

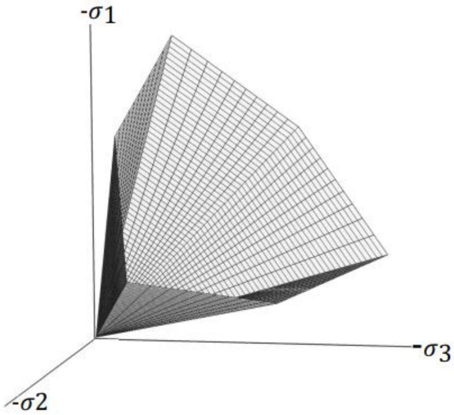

Figure 3: The Mohr-Coulomb yield surface in principal stress space (c = 0) (PLAXIS, 2020)

Table 3: Basic parameters of the Mohr-Coulomb model (after PLAXIS, 2020).

Symbol	Name of the parameter	Unit
E	Young's modulus	[kN/m^2]
ϑ	Poisson's ratio	[-]
C	Cohesion	[kN/m^2]
φ	Friction angle	[°]
ψ	Dilatancy angle	[°]
σ_t	Tension cut-off and tensile strength	[kN/m^2]
G	Shear modulus	[kN/m^2]
E_{oed}	Oedometer modulus	[kN/m^2]
V_p	Compression wave velocity	[m/s]
V_s	Shear wave velocity	[m/s]

3.4 Soft Soil model

The Soft Soil model is a Cam-Clay type model especially meant for primary compression of near normally consolidated clay-type soils. Most soft soil problems can be analyzed using The Hardening Soil (HS) model, but the Hardening Soil model is not suitable the soil is very soft, with a high compressibility ($E_{oed}^{ref}/E_{50}^{ref}$ < 0.5). For such soils, the Soft Soil model may be used. Figure 4 presents the total yield contour of Soft Soil model in principal stress space and Table 4 presents the parameters of the Soft Soil model.

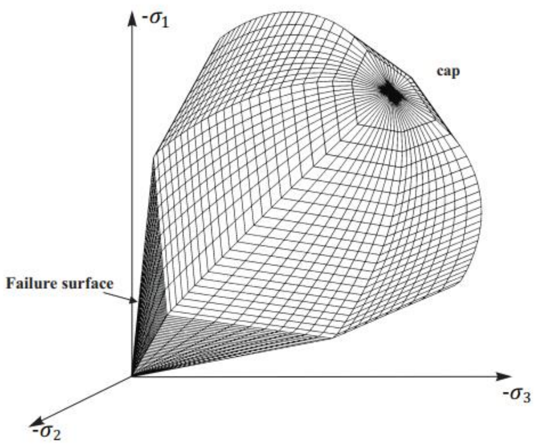

Figure 4: Soft Soil model total yield contour representation in major stress space (PLAXIS, 2020).

Table 4: Basic parameters for Soft Soil Model (PLAXIS, 2020).

Symbol	Name of the parameter	Unit
C	Cohesion	[kN/m^2]
φ	Friction angle	[°]
c_c	Compression Index	[-]
c_s	Swell Index	[-]
ψ	Dilatancy angle	[°]

4. Numerical Study of Satkhira Polder embankment

10-node tetrahedral soil elements is used in PLAXIS 3D. For this study, Soft Soil model was used to model Silty clay and Mohr-Coulomb soil model was used to model Fine Sand soil. Plain strain condition was used for PLAXIS FEM mesh in this study. The range of the model is 35m in vertical direction, 110 m in horizontal direction and 2m in width. No horizontal and vertical displacement were allowed at the bottom boundary, and no displacement is allowed in horizontal directions for vertical mesh boundaries. The ground surface and the bottom boundary of the drainage boundary condition were both drained (in z direction), whereas the drainage boundary conditions along the width were undrained (y direction), and along the center line (x direction) of the embankment drainage conditions were drained. The estimated soil parameters necessary for Satkhira Polder embankment are presented from Table 5.

Table 5: Properties of soil for Satkhira Polder Embankment Stability Analysis

Soil location	Thickness (m)	Soil Type	Soil model	Cohesion C′ (kN/m^2)	Angle of Friction φ'(degree)	Shear Wave Velocity (V) (m/sec)	Shear Modulus (Mpa)	Compression Index (c_c)	Swelling Index (c_s)
Embankment	3.5m	Silty Clay	Mohr-columb (Undrained)	10	24	123	25	-	-
Sub-soil (Layer 1)	4m	Silty Clay	Soft Soil	10	24	123	25	0.157	0.029
Sub-soil (Layer 2)	10.5m	Fine Sand	Mohr-columb (Drained)	6	23	131	30	-	-
Sub-soil (Layer 3)	12m	Fine Sand	Mohr-columb (Drained)	0	35	263	120	-	-

4.1 Staging on embankment model

Construction of the embankment in the project is done in different phases to allow the soil layers to consolidate. PLAXIS 3D facilitates the model to construct the embankment in different stages and allows time to consolidate. The embankment was modeled in three stages where in every stage the constructed part was rested for consolidation settlement. This option was used to represent the real project condition in both embankment model cases. At the Initial Phase only the subsoil layers were created. At the first stage 1.25m of the constructed embankment, allowing 7 days for Plastic analysis. In the subsequent phase the constructed embankment was allowed to consolidate for 30 days. In second stage embankment was constructed from 1.25m to 2.5m for 7 days and allowed 30 days for consolidation. In third stage the embankment was constructed upto 3m for another 7 days and consolidated for 30days. Figure 5 presents the stages of embankment analysis.

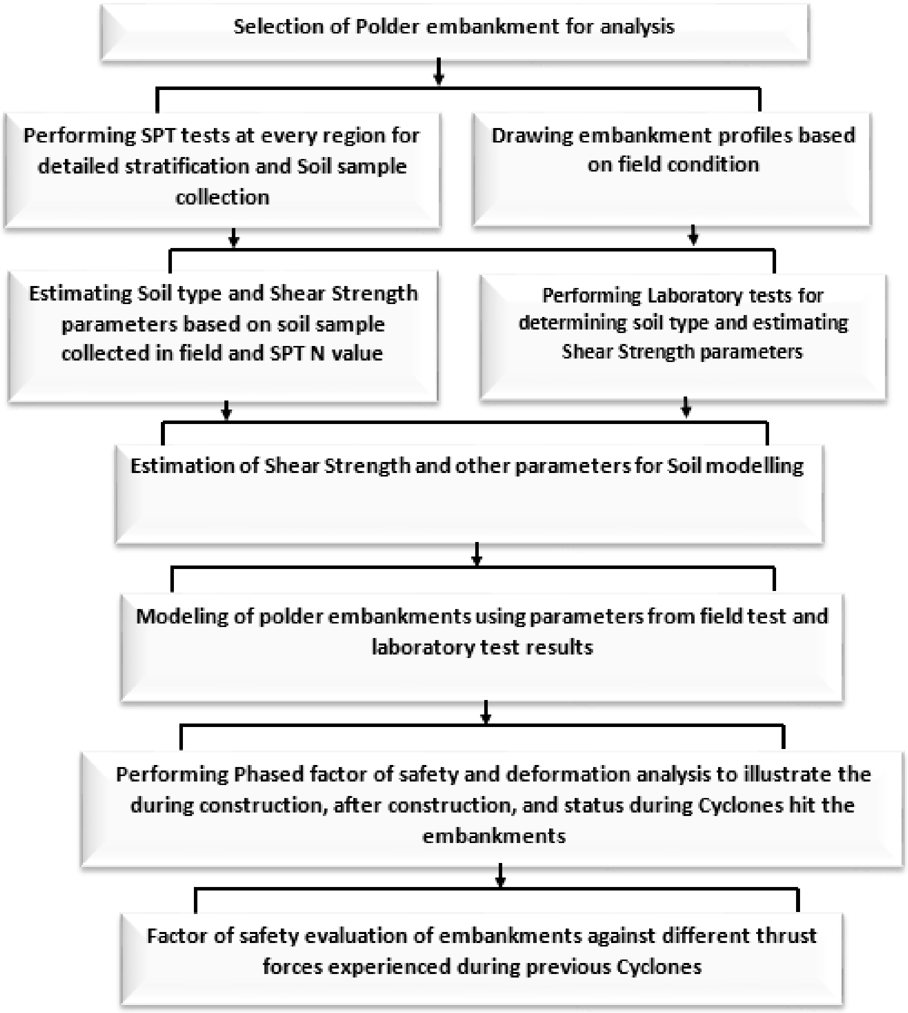

Figure 5: Stages of embankment analysis

5. Result of Analysis

After the completion of embankment construction, the safety status and settlement potential was checked for consolidation analysis. Then, the embankment model was analyzed for rapid drawdown and slow drawdown. Table 6 presents the recommended factor of safety by the U.S. Army Corps of Engineers' slope stability manual.

Table 6: Factor of Safety Criteria from U.S. Army Corps of Engineers' Slope Stability Manual (U.S. Army Corps of Engineers', 2003).

Types of slopes	For End of Construction	For Long-Term Steady Seepage	For Rapid Drawdown
Slopes of dams, levees, and dikes, and other embankment and excavation slopes	1.3	1.5	1.0-1.2

Recently, the region was hit hard against the cyclone SIDR. The improved embankment was analyzed against the surge height and thrust forces against the pseudo cyclone like SIDR to assess its safety status. The results are presented in Table 7 and 8.

Table 7: Safety status of Satkhira embankment for different conditions

Embankment Soil 3.5 m (Silty Clay)		**Analysis type**	**Time**	**Total Displacements**	**Factor of Safety**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	Consolidation	Days	mm	
10	24	Safety after construction	75	162	1.81
10	24	Rapid Drawdown (5.5m to 0m)	7	57.4	1.58
10	24	Slow Drawdown (5.5m to 0m)	30	79.5	1.68
10	24	High water level to very low water level(4.5m to -4.5m)	100	129.5	1.79

Table 8: Safety status of Satkhira Polder embankment for different surge height and thrust forces (SIDR).

Embankment Soil 3.5m (Silty Clay)		**Surge Depth (m)**	**Thrust Force (kN/m)**	**Factor of Safety (FS)**	**Total Displacement**
Cohesion C (kN/m^2)	Angle of Friction φ'(degree)	From bottom of Embankment	Cyclone SIDR		(mm)
10	24	3	1.39	1.86	162.1
10	24	3.5	3.3	1.52	144.5
10	24	2.15	0.8	1.77	146.2

The figures of Satkhira Polder analysis results are presented from Figure 6 to 24.

5.1 Consolidation Analysis

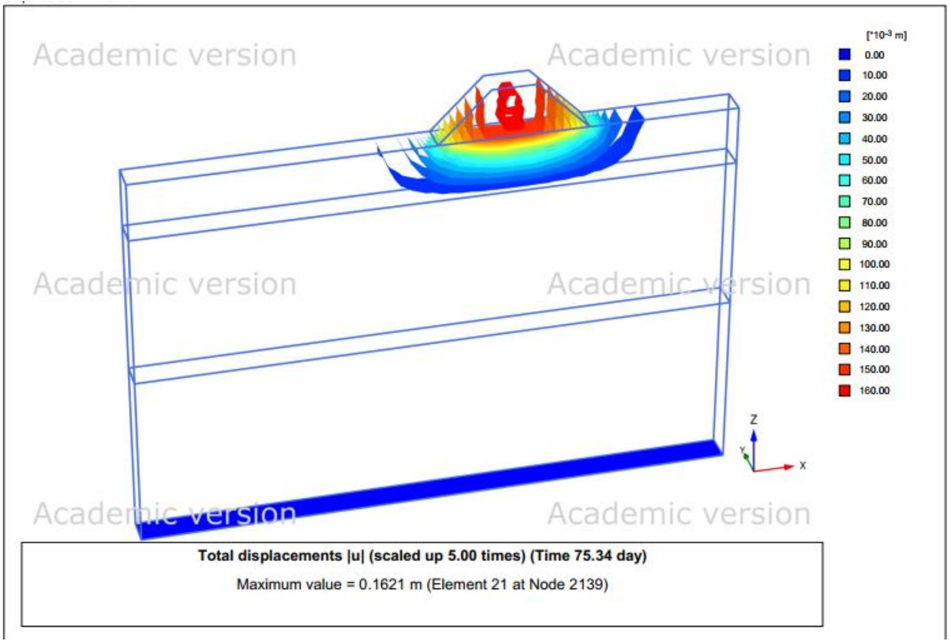

Figure 6: Consolidation settlement of Satkhira Polder

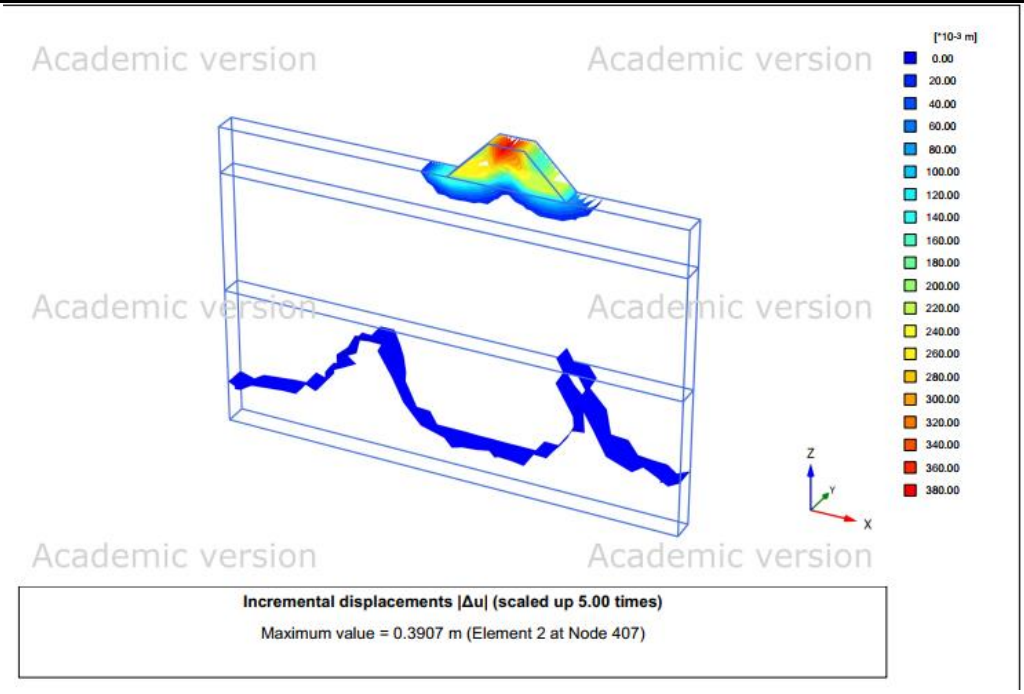

Figure 7: Likely Failure Mechanism for Consolidation settlement of Satkhira Polder

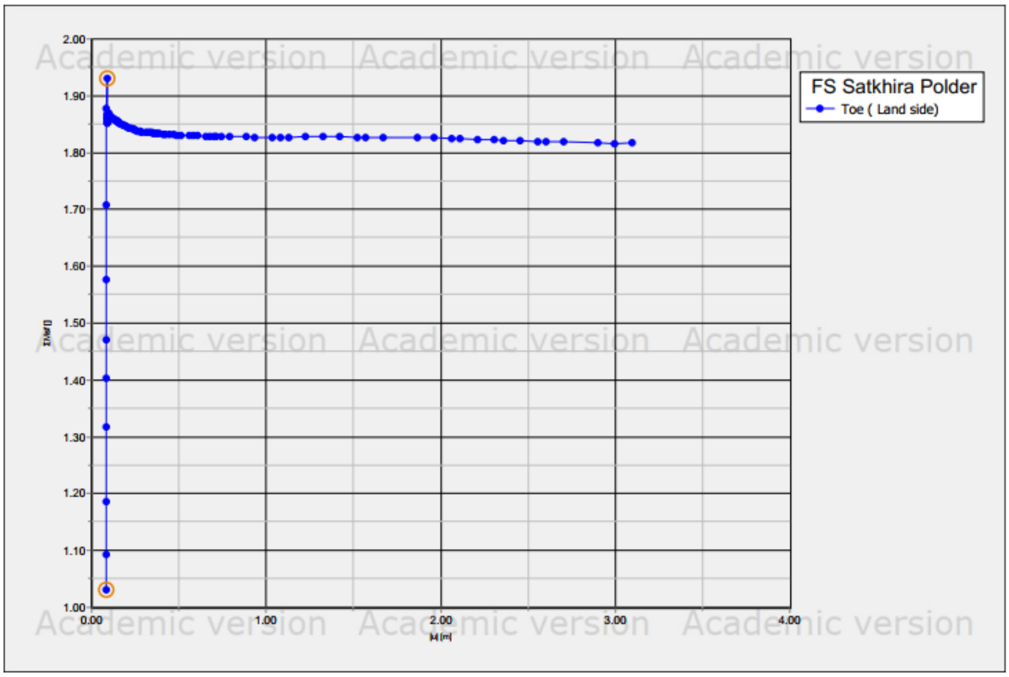

Figure 8: Consolidation Factor of Safety of Satkhira Polder

5.2 Rapid Drawdown (7 Days)

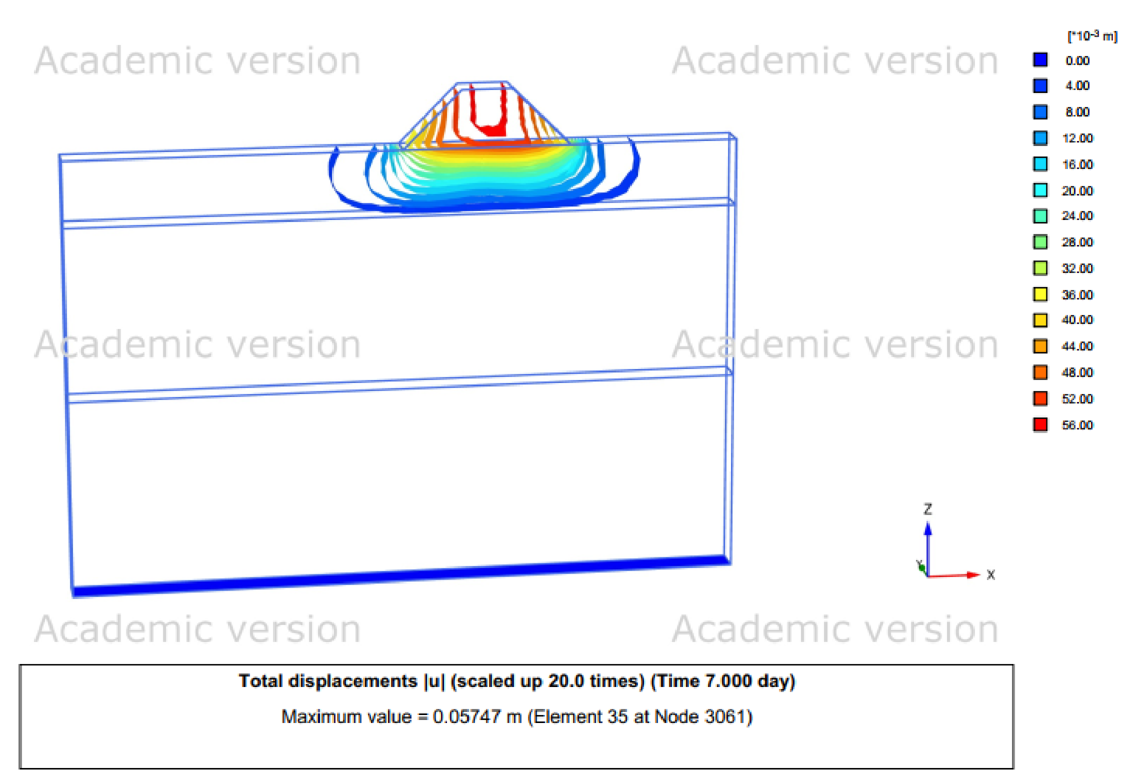

Figure 9: Rapid Drawdown settlement of Satkhira Polder

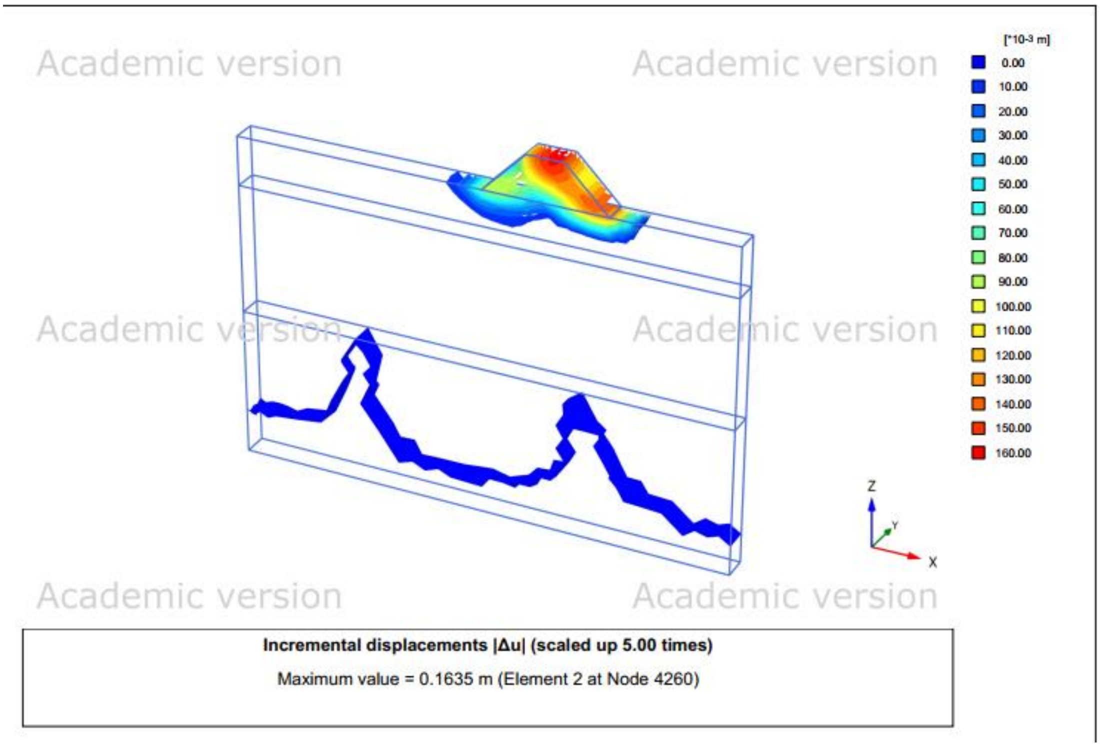

Figure 10: Likely failure mechanism for Rapid Drawdown condition of Satkhira Polder

5.3 Slow Drawdown (30 Days)

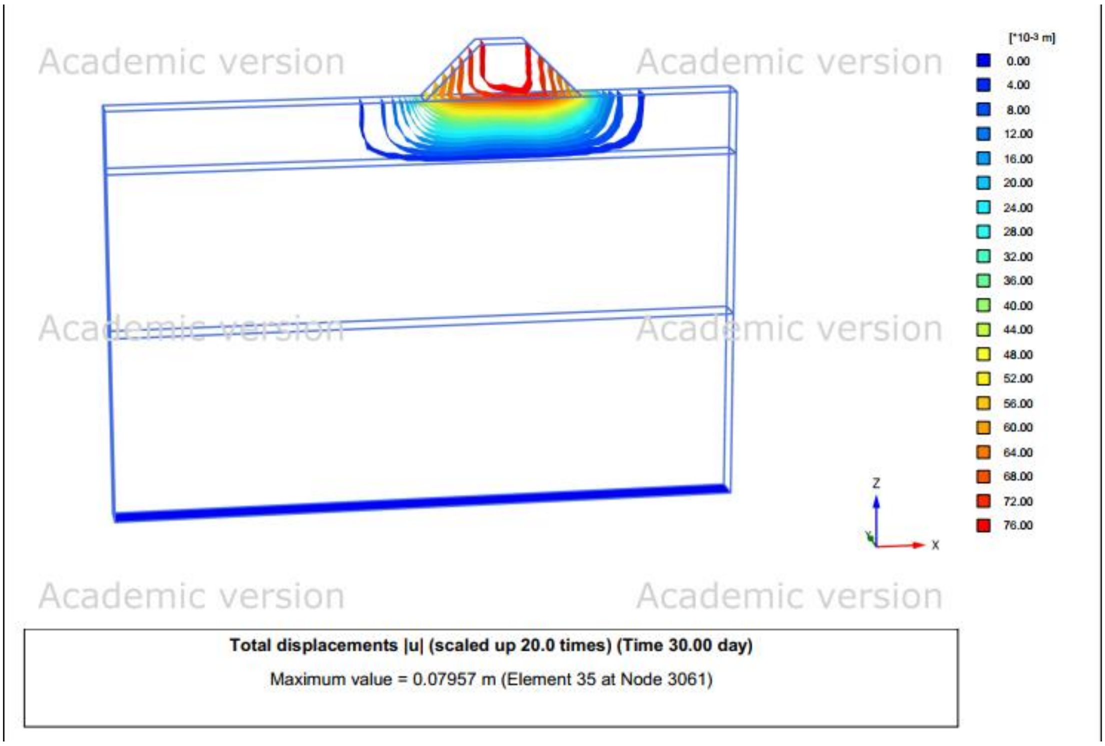

Figure 11: Slow Drawdown settlement of Satkhira Polder

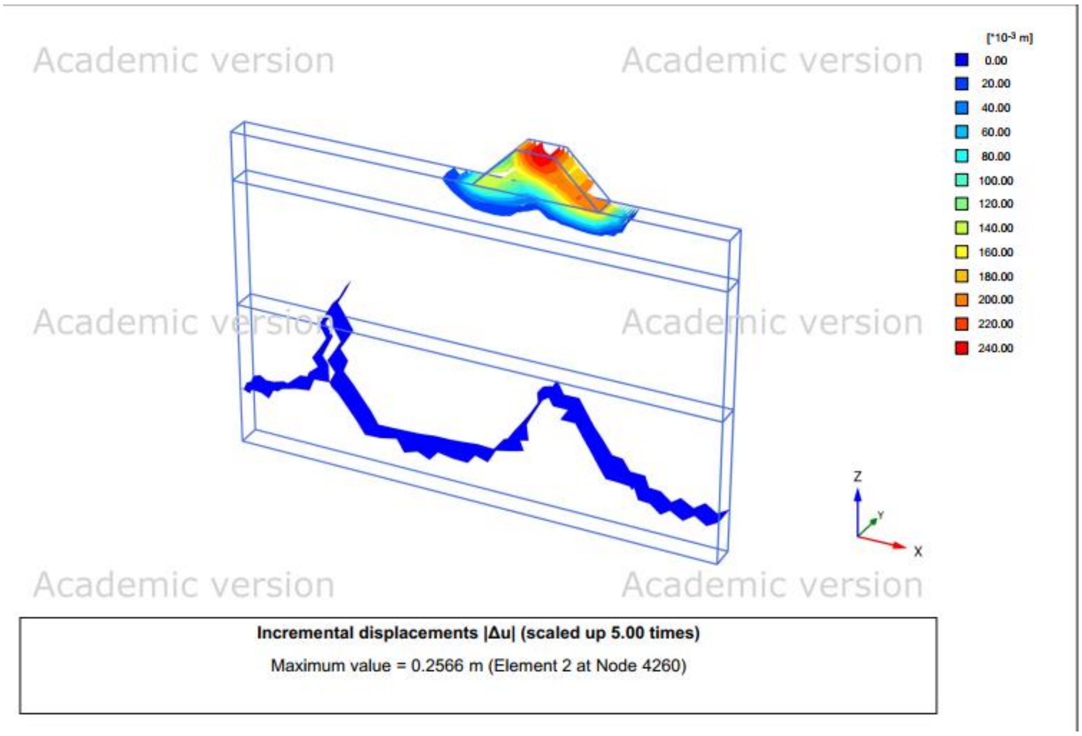

Figure 12: Slow Drawdown likely failure mechanism of Satkhira Polder

5.4 Change in water level (high level to borehole level) over time (100 days)

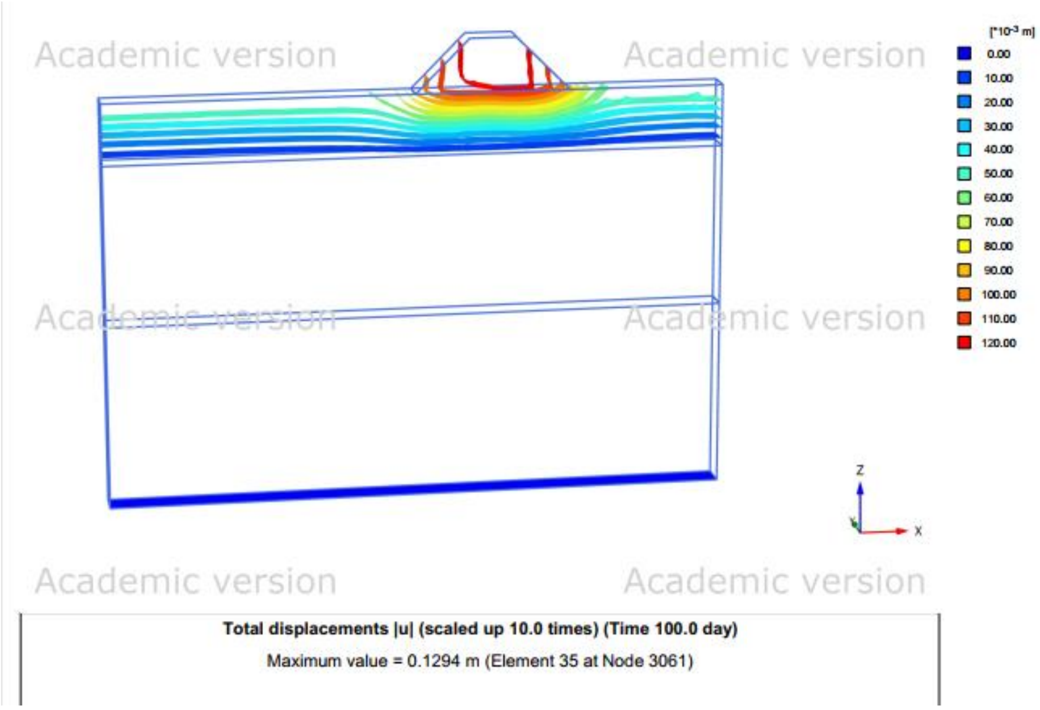

Figure 13: Change in water level (high level to borehole level) settlement of Satkhira Polder

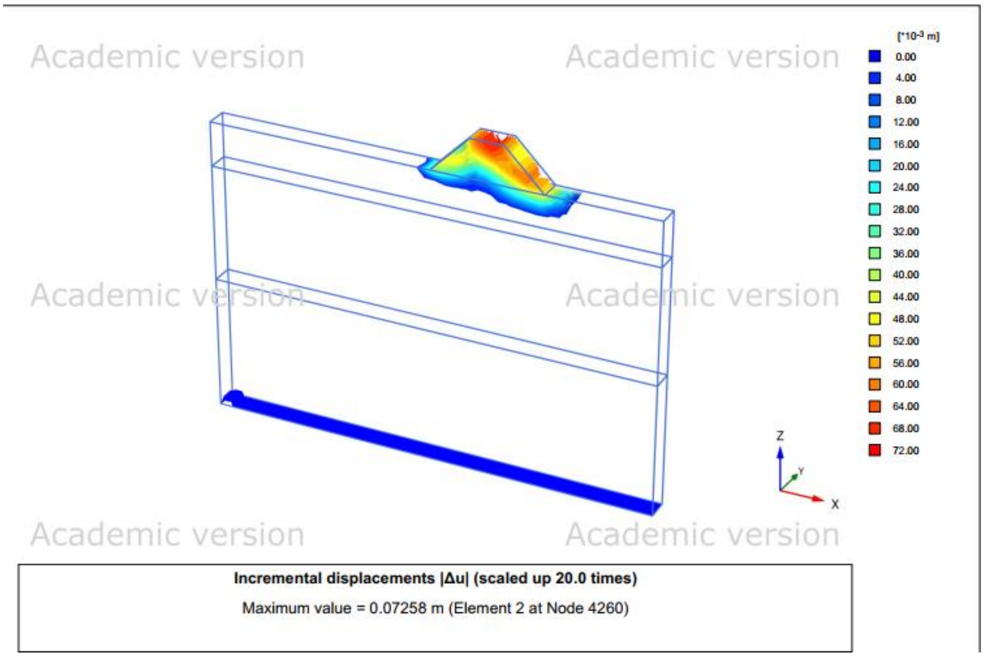

Figure 14: Likely failure mechanism of change in water level (high level to borehole level) of Satkhira Polder

5.5 Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Satkhira Polder

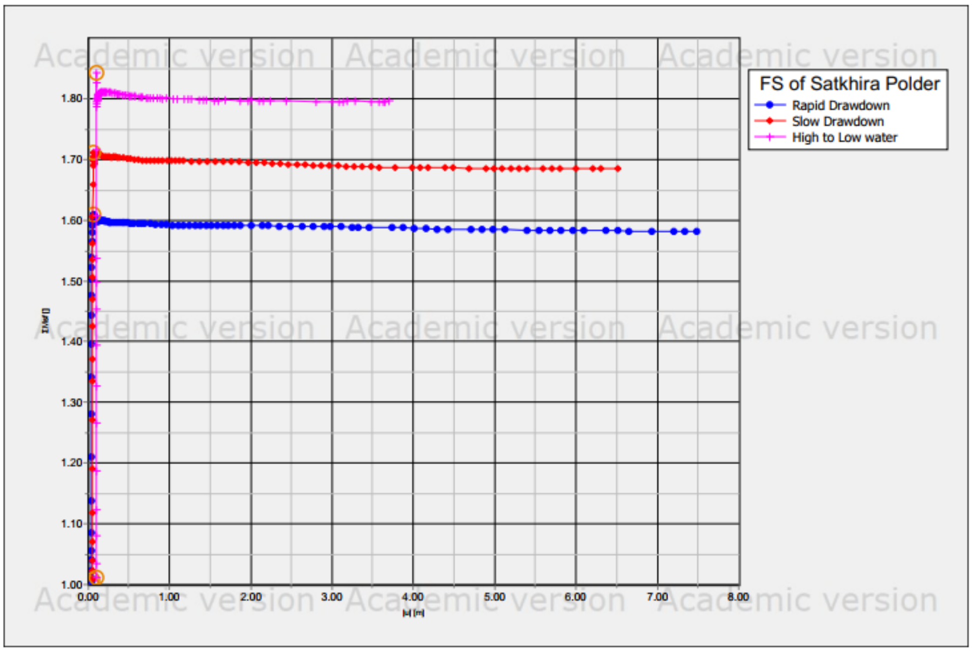

Figure 15: Factor of safety of Rapid Drawdown, Slow Drawdown, and change in water level (high level to borehole level) of Satkhira Polder.

5.6 Analysis result of Satkhira Polder against Cyclone SIDR

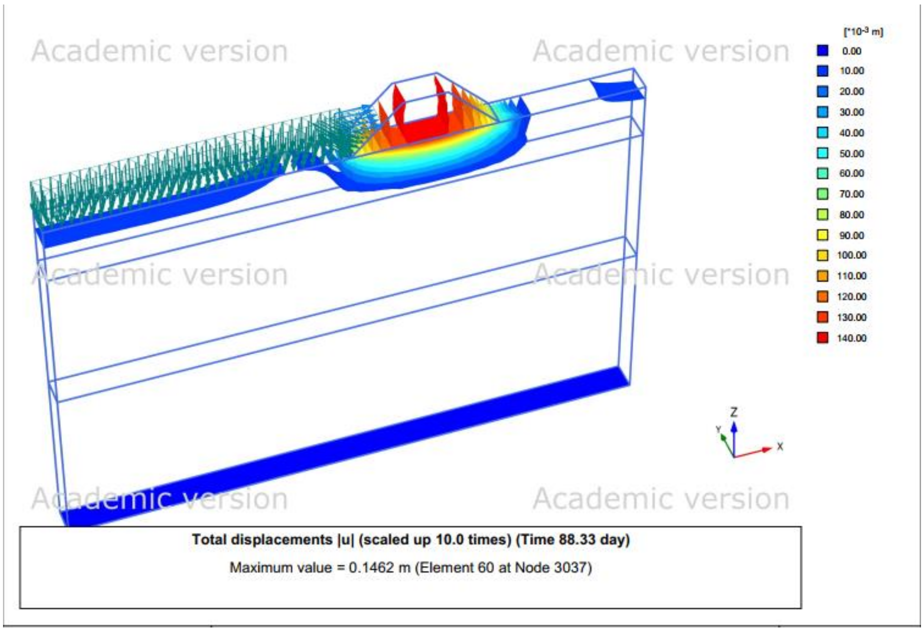

Figure 16: Total Settlement for Surge height 0.8m and thrust force 2.15 kN for Satkhira Polder

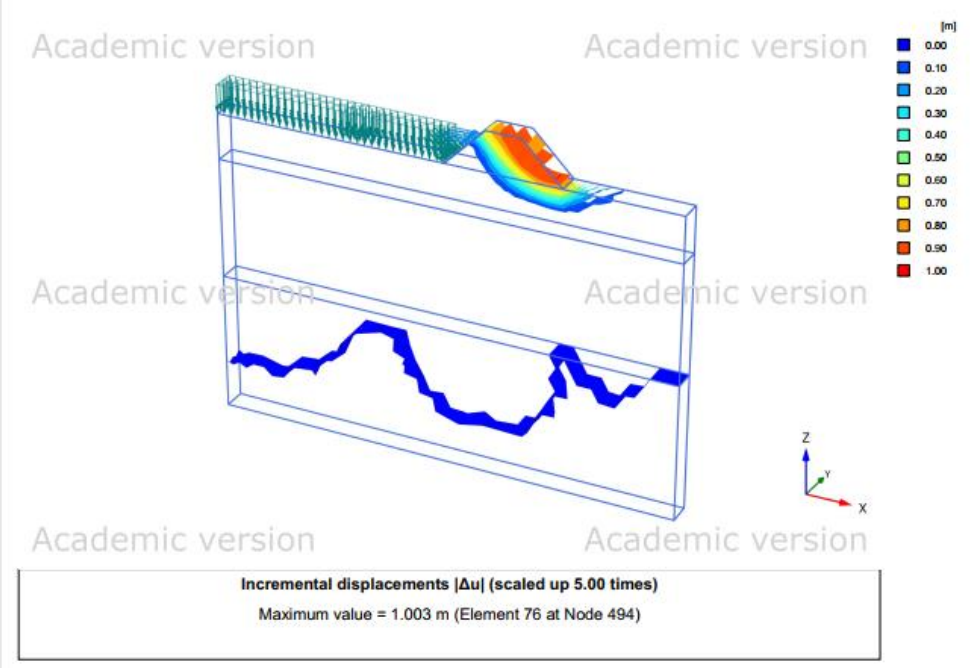

Figure 17: Likely Failure Mechanism for Surge height 0.8m and thrust force 2.15 kN for Satkhira Polder

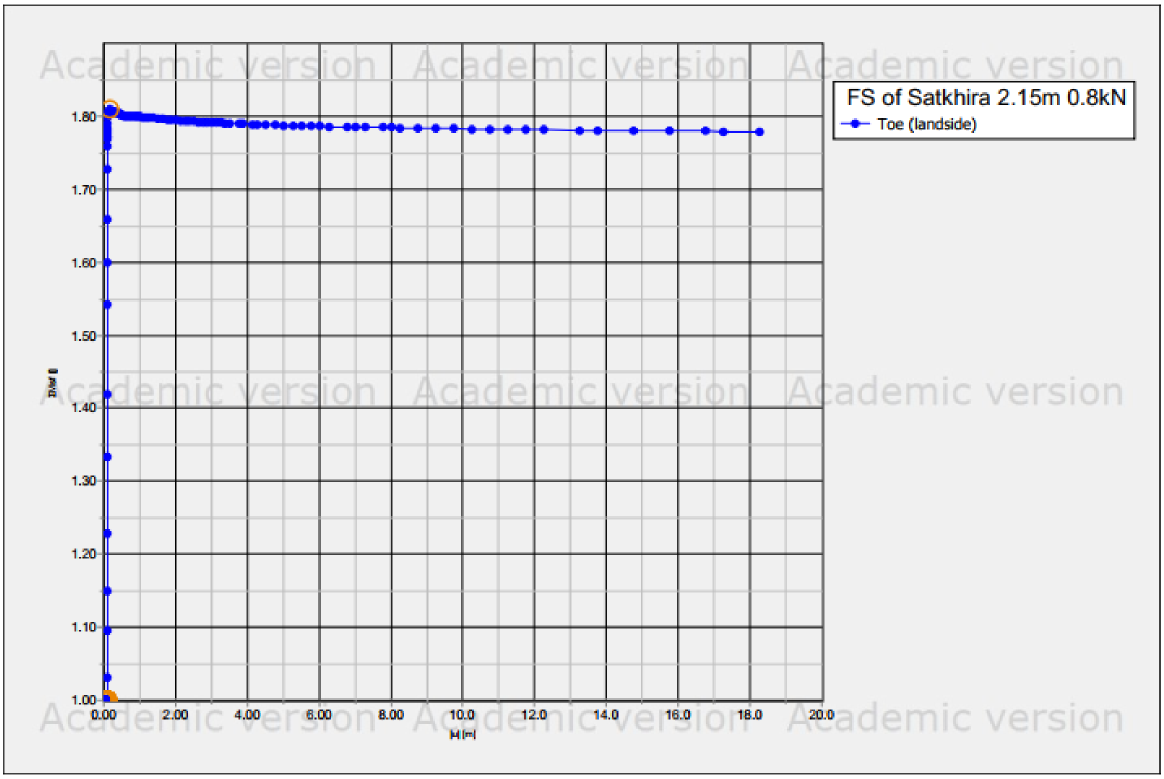

Figure 18: Factor of safety for Surge height 0.8m and thrust force 2.15 kN for Satkhira Polder

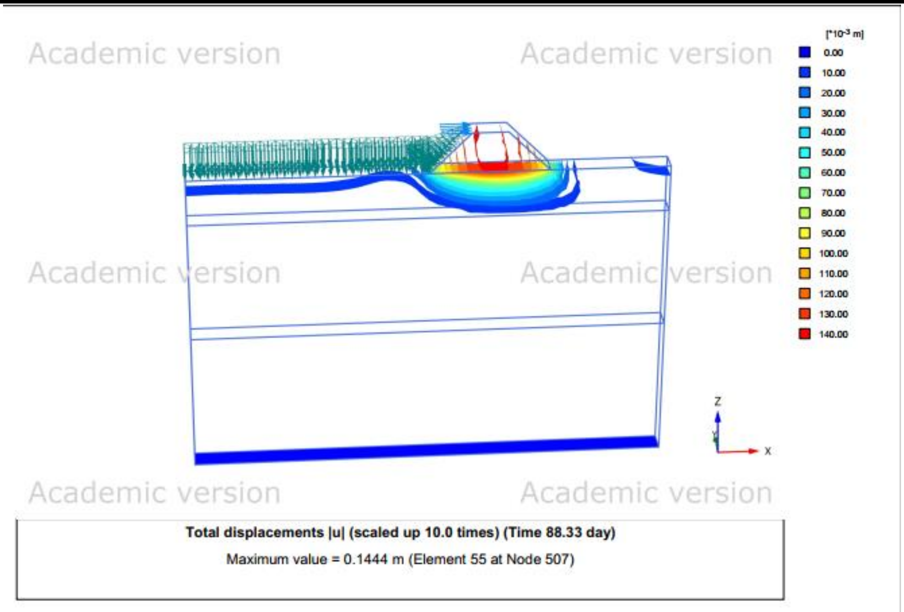

Figure 19: Total Settlement for Surge height 3.3m and thrust force 3.5 kN for Satkhira Polder

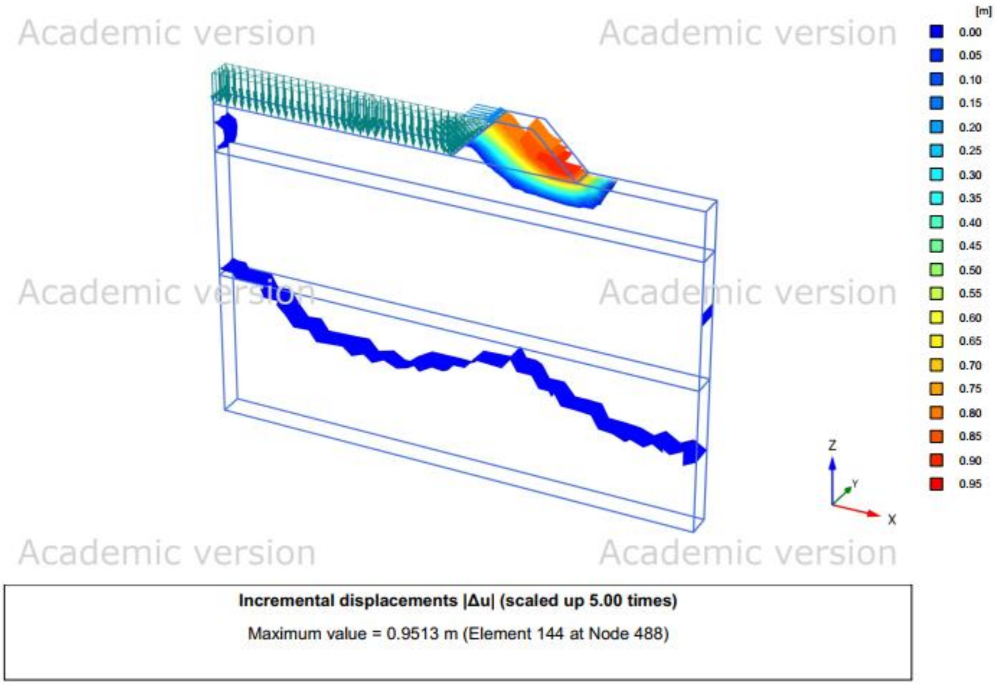

Figure 20: Likely Failure Mechanism for Surge height 3.3m and thrust force 3.5 kN for Satkhira Polder

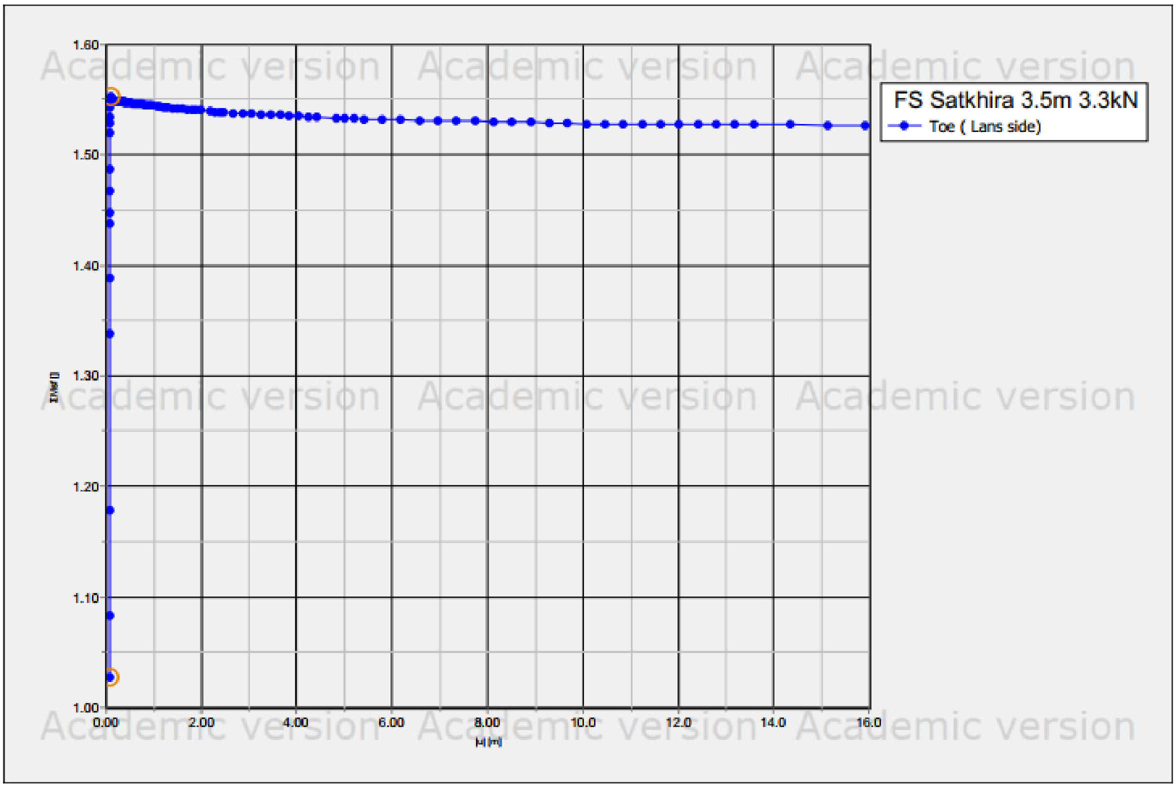

Figure 21: Factor of safety for Surge height 3.3m and thrust force 3.5 kN for Satkhira Polder

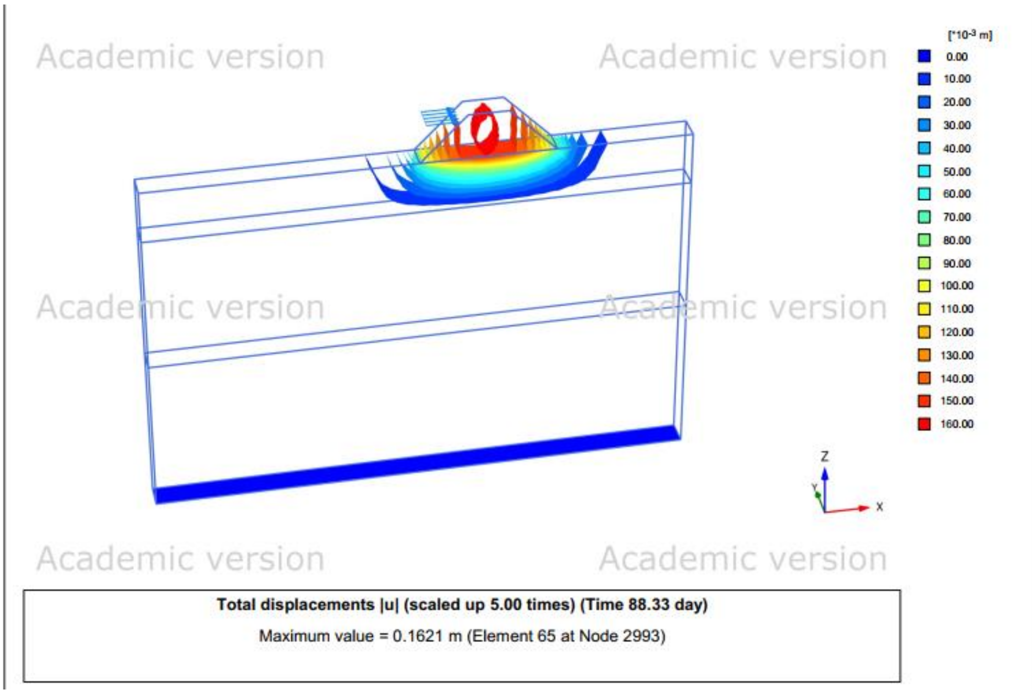

Figure 22: Total Settlement for Surge height 3.0m and thrust force 1.39 kN for Satkhira Polder

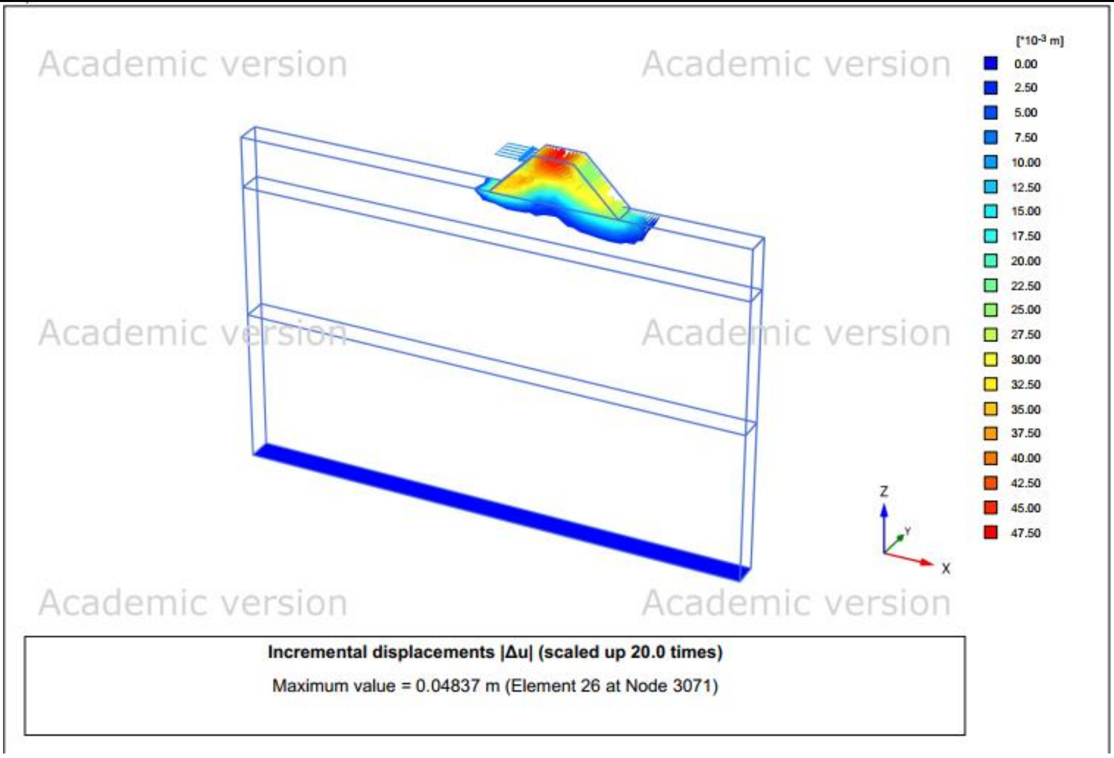

Figure 23: Likely Failure Mechanism for Surge height 3.0m and thrust force 1.39 kN for Satkhira Polder

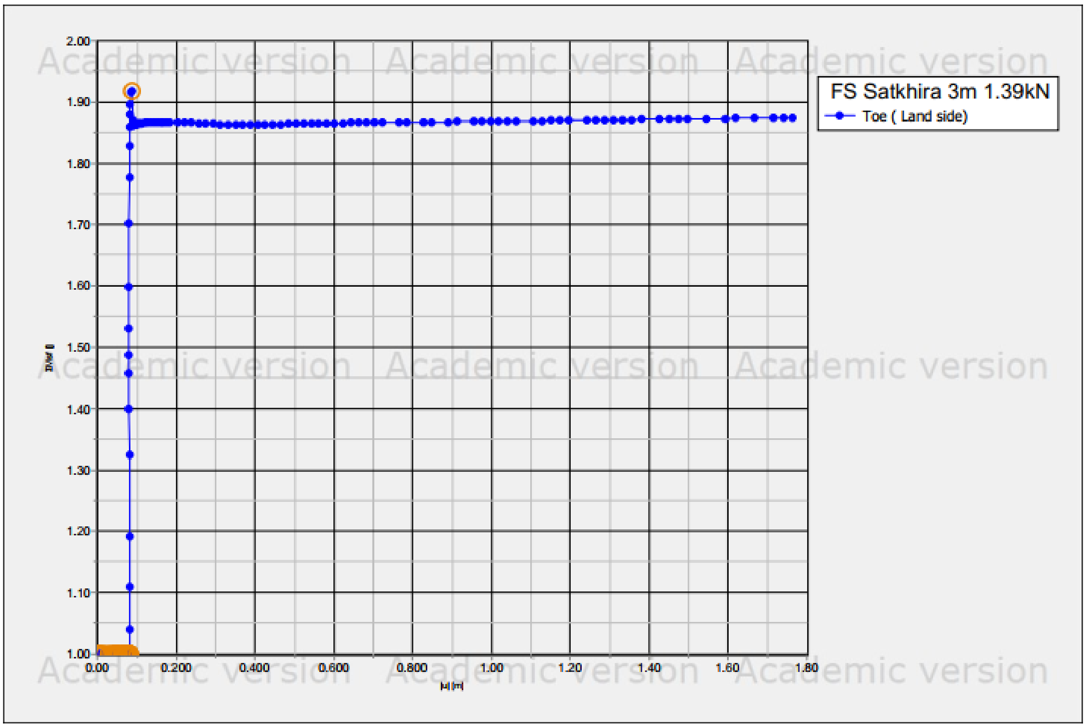

Figure 24: Factor of safety for Surge height 3.0m and thrust force 1.39 kN for Satkhira Polder

6. Conclusion and Recommendation

The coastal zones of Bangladesh are severely affected by cyclones and storm surges every year. The government of Bangladesh has taken initiatives for the improvement of coastal Polder embankments to safe the area against the disastrous effect of the natural calamities through Coastal Embankment Improvement Program (CEIP). This study was confined to assess the stability of Polder embankment at Satkhira, based on geotechnical parameters extracted through SPT test, laboratory investigation and empirical correlations. A finite element based program, PLAXIS 3D, was used in the study for assessing the safety status of the Polder embankment. Results show that the safety condition of the embankment has improved after the initiative of CEIP. As the geotechnical parameters and section of embankment can vary along the Polder, geotechnical investigations and laboratory testing should be performed for more locations to study the stability conditions. Again, due to weathering conditions the affecting parameters related to safety condition of the embankment might change; thus periodic study would be necessary to continuously monitoring the safety condition of the Polder embankment.

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