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Analysis and Simulations of Flood Control Dikes and Erosion Protection Schemes using PLAXIS FEM 2D and SLIDE Softwares

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ABSTRACT: In 2011, Thailand has suffered from devastating flooding due to climate change. During this time, 2 typhoons from the Pacific area went straight across Vietnam to Northern Laos and Northern Thailand instead of the usual path to Taiwan and Japan. Subsequently, huge flooding damaged many infrastructures and overtopped flood protection dikes of many industrial estates and educational institutions in the Central Plain of Thailand such as at Hi-Tech Industrial Estate, Bang Pa-In Industrial Estate, Navanakorn Industrial Estate and Asian Institute of Technology. The same phenomenon also occurred in Laos PDR which caused unusually heavy rains and widespread river flooding in 2011. Consequently, slope failures occurred along National Road 1B (NR 1B) in Pongsaly Province in Northern Laos due to undercutting erosions at the lower slopes by the adjacent flooded river. To evaluate the stability of these protection structures, finite element and limit equilibrium methods were utilized. PLAXIS 2D software was used to analyze the slope stability of improved flood protection dikes and erosion control schemes at low and high water levels incorporating the various supporting and reinforcing materials such as geosynthetics, concrete sheet pile and concrete slab. Moreover, the PLAXIS 2D software was also utilized to predict the vertical deformations (settlements) of improved flood protection dikes in cases of additional embankment height and at different cases of flood water levels. In addition, the SLIDE software was used to predict the value of the factor of safety by using limit equilibrium method for the improved flood protection dikes and erosion control schemes.

KEYWORDS: Flood, Erosion, Finite element, Limit Equilibrium, Bangkok, Lao PDR, Embankment

1. INTRODUCTION

Flooding occurs when the water level in a creek, river, lake or the sea rises and submerges land that is usually dry which mostly occur in low and flat area. The common cause of flooding is due to heavy rainfall which also increase the water flow of rivers.

To prevent from flooding problem, a dike or embankment is usually constructed along the banks of a stream, river, beach and lake for protecting the landside from overflowing of water. The water level should be considered for the design of the dike, which ground level is considering in the setting of flood level. Thus, the dike level should be higher compared to the surrounding areas. In some cases, the concrete retaining wall may be installed for flood prevention (increase the height of the structure). (Department of Public Works and Highways Japan International Cooperation Agency, 2010)

To construct the flood protection structures on hard subsoil or next to riverbank area, the problem that usually arises is erosion. Erosion mechanism consists of detachment, transport, and deposition (Choi et al, 2002)). In addition, the construction of flood protection dikes on soft subsoil, vertical deformation or settlement problem can usually occurs.

To improve the stability of the structures, many techniques have been introduced such as the application of geosynthetics, which are planar products manufactured from polymeric materials that can be used with soil, rock, or other geotechnical-related materials. Geosynthetics have many functions such as filtration, drainage, separation, and reinforcement. Hence, the use of geosynthetics in flood protection dike is not only for improving the stability of the dike as reinforcement but also for the purpose of erosion control. For example, erosion control geomat (ECGM) (Yee, 2012) is widely used in flood dike which is a rolled ground-covering product that helps or prevents or retards the erosion process. Another example is for the case of erosion along shoreline, the geotextile container revetments have been widely used to prevent from erosion and change of the beach profile (Chua et al, 2012).Vegetation technique can provides a protective cover to the ground against surface erosion with lower cost but less effective if compare to geosynthetics. Moreover the combinations of techniques are also applicable depending on the design of the dike and requirement in certain locations and situations.

In 2011, severe flooding occurred in Thailand due to climate change. The heavy flooding was caused by the abnormal arrival of 2 typhoons in Northern Thailand which otherwise go to Taiwan and Japan. These floods spread throughout the northern provinces and eventually reached in the Bangkok area and caused destruction of infrastructures. Many flood protection structures around Bangkok area were overtopped and damaged by this flood disaster such as at Hi-Tech Industrial Estate, Bang Pa-In Industrial Estate, Navanakorn Industrial Estate and Asian Institute of Technology, etc. Consequently, re-construction were done in the flood protection dikes with different improvement techniques to prevent flooding in the near future.

In 2011, the unusually heavy rains due to the abnormal storms caused the slope failures along the National Road 1B (NR 1B) along the portion passing through the soft shale area from KM 90 to 103 in Phongsali Province, Northern Lao PDR. Four different sites were investigated and were reinforced with geosynthetics mainly for improvement of slope stability and erosion control at riverside.

The objective of this paper is to evaluate the various improvement of flood protection dikes and erosion control schemes using different techniques (geosynthetics, vegetations and sheet piling) and evaluate which design has the capability in terms of slope stability and deformations by using PLAXIS FEM 2D and SLIDE Limit Equilibrium Softwares.

2. STUDY AREAS

The selected study areas improved flood protection dikes in this paper are located north of Bangkok, which is located in the Chao Phraya Delta in central part of Thailand. The stratigraphy of Chao Phraya Delta contains of thick Pleistocene, thin Holocene and recent fluvial deposits. The Quaternary deposits of Bangkok subsoil come from the deposition at the delta of the ancient river in the Chao Phraya Plain. During the flood crisis in Bangkok in the year 2011, the overtopping of flood protection dikes at 4 different sites occurred at Hi-Tech Industrial Estate, Bang Pa-In Industrial Estate, Navanakorn Industrial

Estate and Asian Institute of Technology. Besides the overflow, seepage of water through the flood control dikes were also observed (IEAT, 2012).

2.1 HI-TECH INDUSTRIAL ESTATE

Hi-Tech Industrial Estate is located on the Asian Highway in Ayutthaya Province. The elevation inside Hi-Tech Industrial Estate is +1.400 MSL, around the area was protected by earth embankment with 10 m wide at the base and 3 m wide at the crest with height of +2.70 above MSL. Due to the flooding in 2011, IEAT ordered the evacuation of all workers in the Ayutthaya Hi-Tech Industrial Estate due to possible flooding and all factories have been shut down. Initial report indicated that the flood water breached and overtopped the flood protection dikes in the southern portion of Hi-Tech Industrial Estate. The location and dike cross-section at Hi-Tech Industrial Estate is shown in Figure 1. The Industrial Estate Authority of Thailand (IEAT) suggested to increase the height of flood protection barrier from elevation +3.8 00 MSL to +5.400 MSL. The improved flood protection dike used the combination of geotextile, geocell and vegetation technique to improve its erosion resistance and increased its stability. Soil models and parameters of the improved flood protection dike of Hi-Tech Industrial Estate are tabulated in Table 1.

Table 1 Soil models and parameters at Hi-Tech Industrial Estate

Material	Depth (m)	Model	γ_{sat} (kN/m^3)	$2kx=ky$ (m/day)	c' (kPa)	Φ' (º)
Subsoil						
Weathered crust	1-0	MCM	17	0.002	15	25
Soft clay 1	0-6	SSM	15	0.0008	7	23
Soft clay 2	6-8	SSM	15	0.0008	5	23
Soft clay 3	8>	SSM	15	0.0008	5	23
Compacted embankment		MCM	16	0.002	11	26

2.2 BANG PA-IN INDUTRIAL ESTATE

Bang Pa-In Industrial Estate is located in Bang Pa-in, Ayutthaya Province. The elevation inside Bang Pa-In Industrial Estate is +2.550 MSL and protected by flood protection barrier of +3.850-4.100 MSL. In the year 1995, flood crisis occurred with water elevation of +3.500 to 3.800 MSL but the flood protection barrier worked efficiently preventing flood water from breaching into industrial estate area. In 2011, flood waters breached at the east flood prevention wall and all factories were shutdown. IEAT ordered the evacuation of all workers in the Bang Pa-In Industrial Estate due to flooding with height of +4.280 MSL. The location and dike design of Bang Pa-In Industrial Estate is shown in Figure 2. The new dike use a combination of geotextile, RC floodwall and concrete slab for erosion protection and increased stability. IEAT suggested to increase the height of flood protection dike from elevation +3.850 MSL to +5.850 MSL Soil models and parameters used at Bang Pa-In Industrial Estate are tabulated in Table 2.

Table 2 Soil models and parameters at Bang Pa-In Industrial Estate

Material	Depth (m)	Model	γ_{sat} (kN/m^3)	$2kx=ky$ (m/day)	c' (kPa)	Φ' (º)
Subsoil						
Weathered crust	0-2	MCM	19	0.004	20	25
Soft clay 1	2-8	SSM	18	0.0004	5	23
Medium stiff clay	8-10	MCM	19	0.0004	12	27
Compacted embankment		MCM	20	0.0004	12.5	16

2.3 NAVANAKORN INDUTRIAL ESTATE

Navanakorn Industrial Estate is located in Phaholyothin Road, Klong Luang, Pathumthani Province. The elevation inside Navanakorn Industrial Estate is +1.400 MSL and protected by flood protection barrier of +3.506 MSL. In 2011, flood waters overtopped the existing flood protection dikes and flooded into Navanakorn Industrial Estate area. All factories and operations were shut down.

The new dike design in Navanakorn Industrial is using a combination of geotextile, geocell, RC sheetpile and vegetation techniques for improving the stability of the dike. The height of dike was increased to +6.000 MSL with local road on the waterside of industrial estate area. Figure 3 shows the location and new dike design of Navanakorn Industrial Estate. Soil models and parameters of Navanakorn Industrial Estate are tabulated in Table 3.

Table 3 Soil models and parameters of Navanakorn Industrial Estate

Material	Depth (m)	Model	γ_{sat} (kN/m^3)	$2kx=ky$ (m/day)	c' (kPa)	Φ' (º)
Subsoil						
Top soil	0-1	MCM	19	0.002	31	31
Very Soft to Medium	1-9	SSM	16.5	0.0004	3	23
clay	9-12	MCM	19	0.0008	10	26
Stiff to very						
Stiff clay	12>	MCM	21	0.0008	30	27
Stiff clay						
Very Stiff clay						
Compacted embankment		MCM	20	0.002	10	26

2.4 ASIAN INSTITUTE OF TECHNOLOGY (AIT)

The campus of the Asian Institute of Technology (AIT) is located in Klong Luang District, Pathumthani Province, about 40 km north of Bangkok. It was established to promote technological change and sustainable development in the Asian-Pacific region through higher education, research and outreach since 1959.

The elevation inside AIT campus is around +2.000 to 2.300 MSL. The flood occurred in AIT on 21 October, 2011. Before flooding, AIT tried heightening the dikes to elevation +2.400 MSL but finally overtopped by flood waters. The location and new dike design in Asian Institute of Technology is shown in Figure 4 which was constructed with height +4.700 MSL

The general soil profile and basic soil properties at AIT were investigated by Bergado et al (1995) which can be divided into four sublayers such as the weathered crust which consists of heavily over-consolidated reddish-brown clay with depth of 2 m from ground surface, the underlying layer is soft, grayish clay down to 8 m, followed by the 2 m thick layer of medium stiff clay and last layer is stiff clay layer which can be found down to 15m depth (Jamsawang, 2009). Soil models and parameters of AIT are tabulated in Table 4.

Table 4 Soil models and parameters of AIT

Material	Depth (m)	Model	γ_{sat} (kN/m^3)	$2kx=ky$ (m/day)	c' (kPa)	Φ' (º)
Subsoil						
Weathered crust	0-2	MCM	17	0.002	10	23
Soft clay 1	2-4	SSM	15	0.0008	3	23
Soft clay 2	4-6	SSM	15	0.0008	3	23
Soft clay 3	6-8	SSM	15	0.0008	3	23
Medium stiff	8-10	MCM	17	0.0004	10	25
Stiff clay	10-30	MCM	19	0.004	30	26
Laterite		MCM	20	1	11.3	36
Clay layer		MCM	16	0.002	10	26

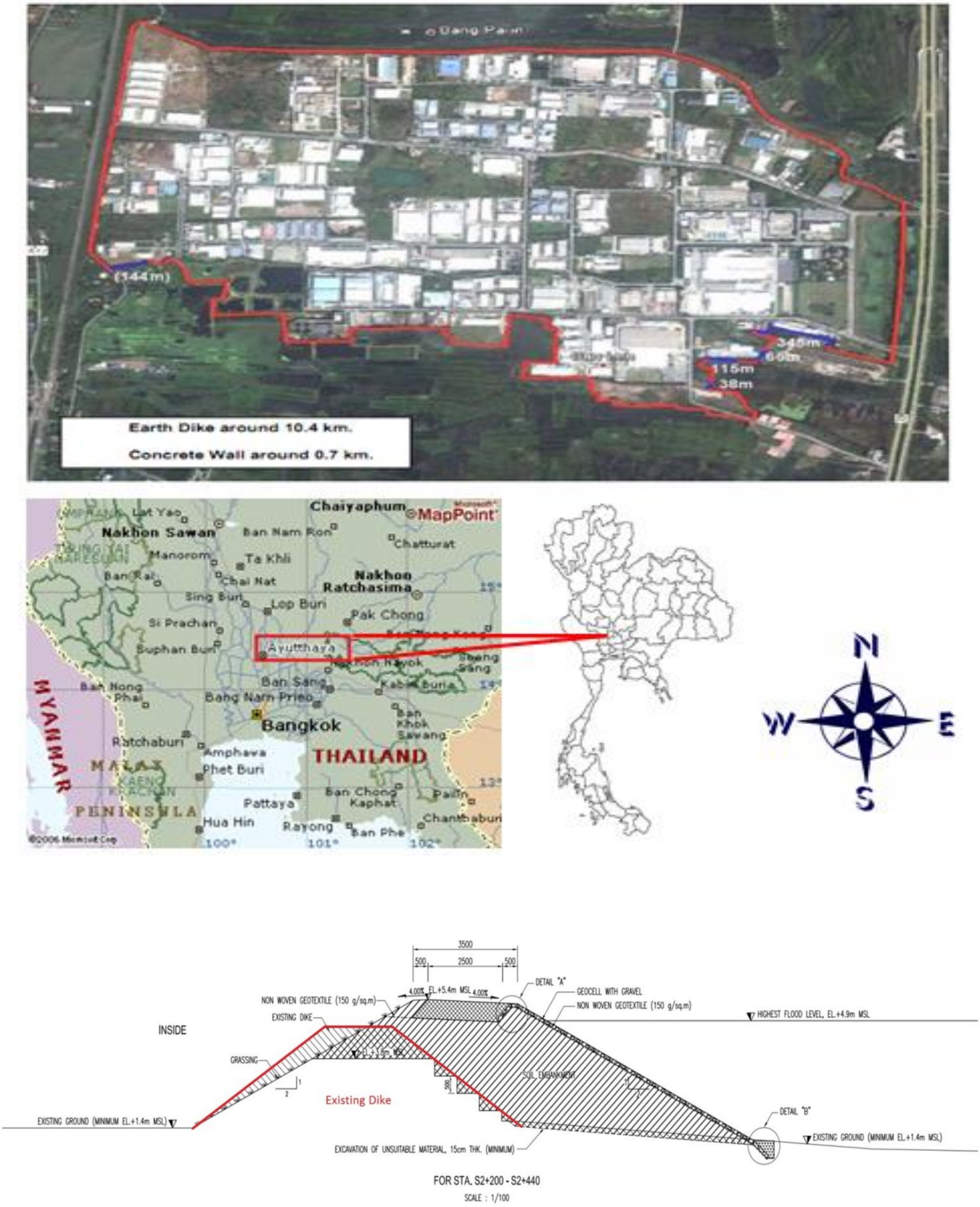

Figure 1 Location and new dike design of Hi-Tech Industrial Estate

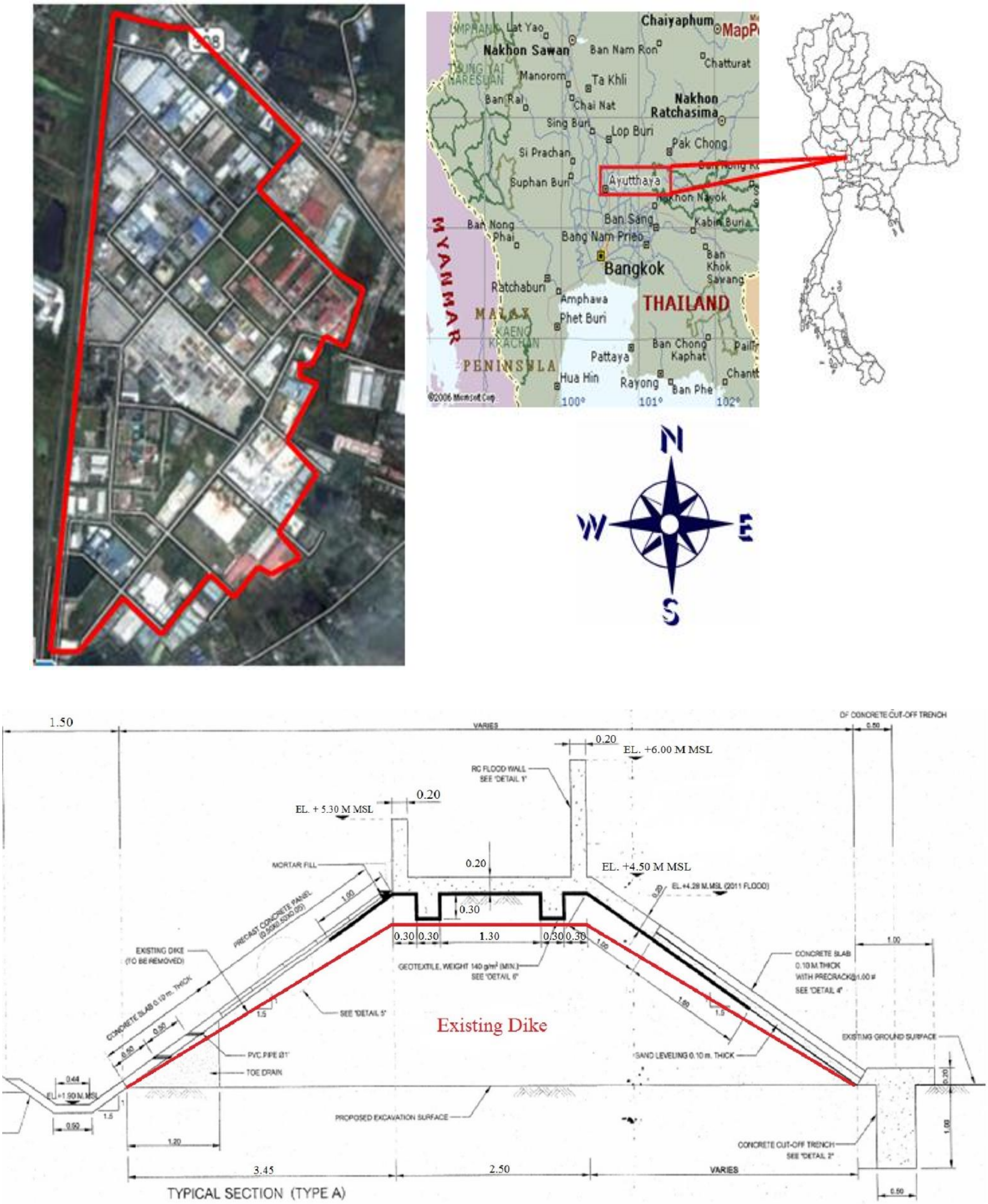

Figure 2 Location and new dike design at Bang Pa-In Industrial Estate

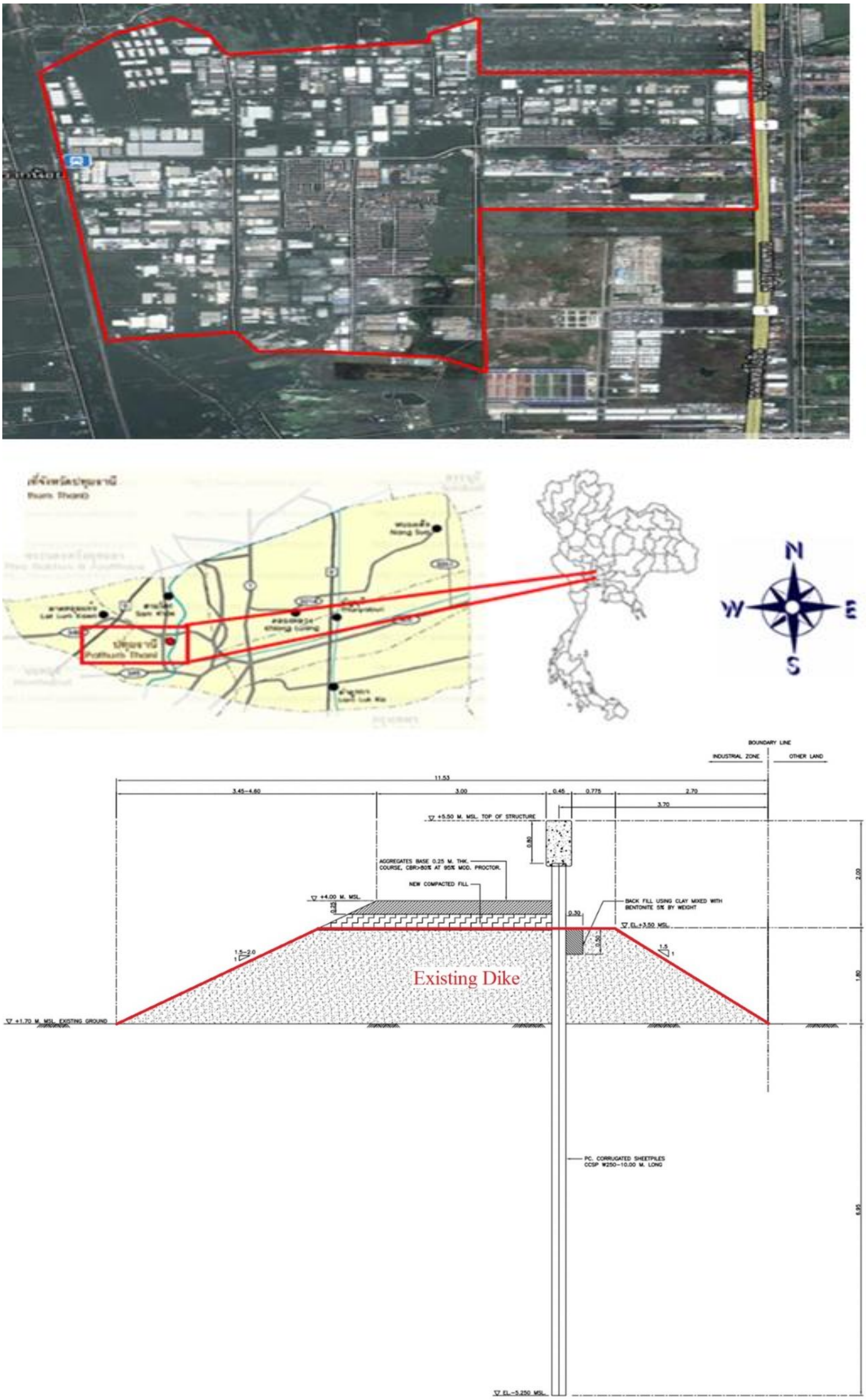

Figure 3 Location and New dike design of Navanakorn Industrial Estate

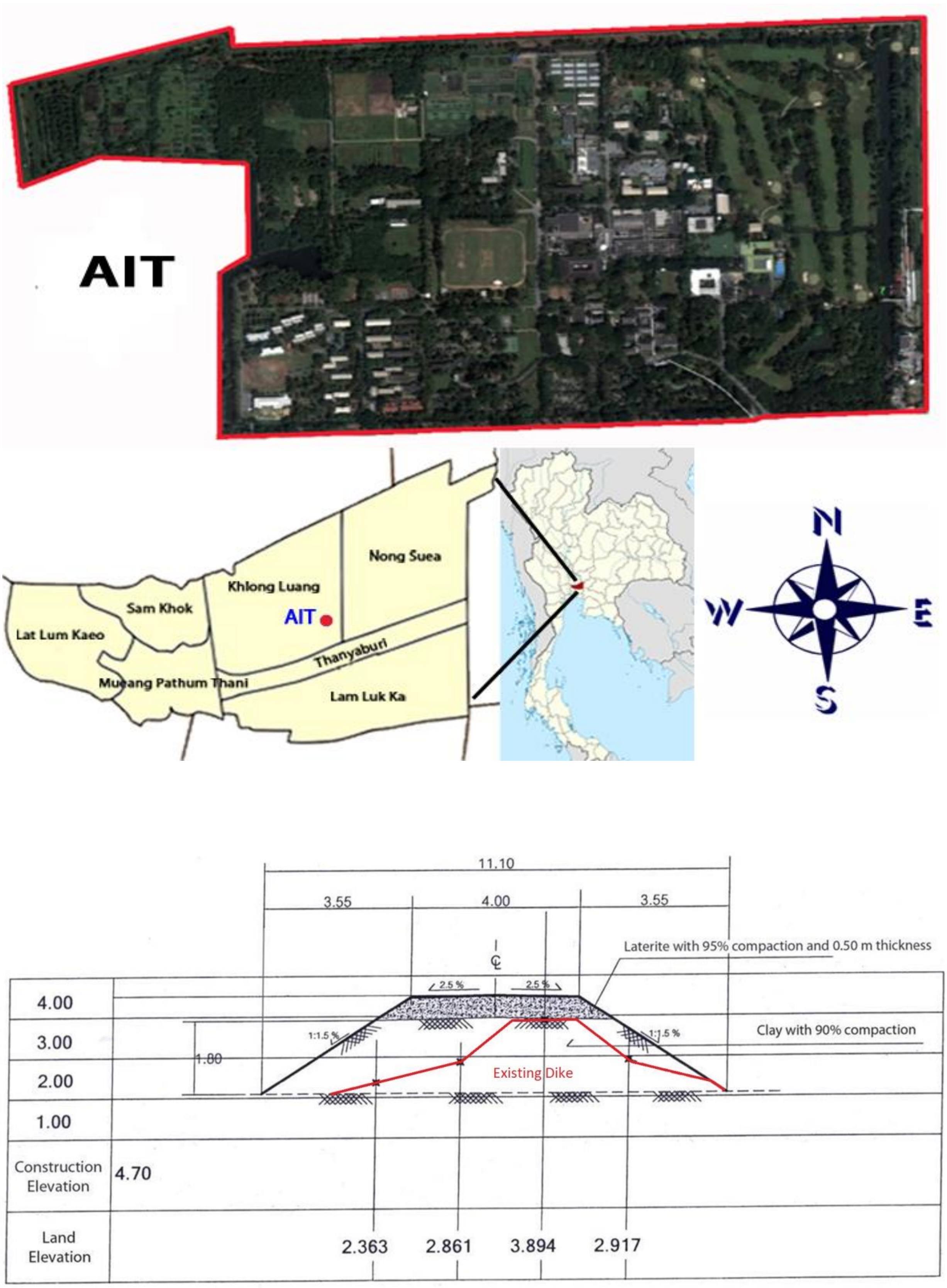

Figure 4 Location and new dike design of Asian Institute of Technology (AIT)

2.5 NATIONAL ROAD 1B (NR 1B) ALONG PHONGSALI PROVINCE IN LAOS PDR

Phongsali Province is mountainous area in northern Laos PDR near the border with China to the north and west and Vietnam to the east. National Road 1B (NR 1B) connects Phongsali Province to China border. It is located high in mountains with approximately 450 to 1,800 m above sea level. Below NR 1B is a river flowing parallel to its alignment (Figure 5).

In 2011, unusually heavy monsoon rains, exacerbated by tropical storms, have caused widespread flooding in more than 60 percent of the Lao PDR especially in the northern part. The monsoon rains continued, and the country endured almost continuous heavy rainfall for some ten weeks (Disaster Relief Emergency Fund, 2013). Consequently, slope failures occurred in National Road 1B (NR 1B) mostly along the portion passing through the soft shale area (KM 90 to 103) in Phongsali Province as shown in Figure 5. Soft shale tends to weather into clayey soils with low shear strength, high compressibility, low permeability and are highly erodible.

Four different stations were investigated, namely: KM90+625 (Figure 6), KM 92+125 (Figure 7), KM 92+212.5 (Figure 8) and KM92+512.5 (Figure 9). The soil model and related parameters are shown in Table 5. The mitigation measures consist of geosynthetic reinforcements (T_{ult} = 150 kN/m) at 0.5 m vertical spacing with rock filled gabions in the lower sections for erosion control. The compacted slope fill consisted of free-draining crushed sandstones.

Figure 5 Erosion at the lower slopes due to river flooding causing slope failures in Phongsali Province, Northern Laos PDR

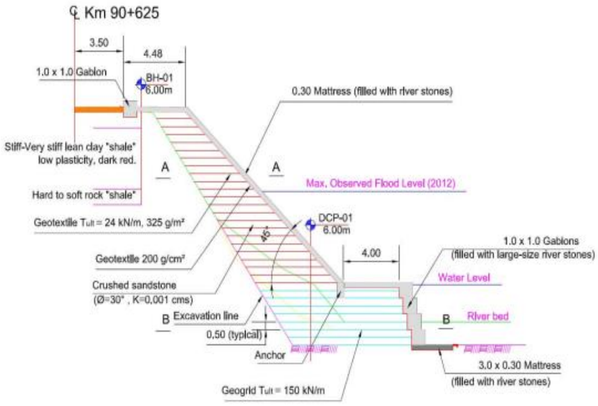

Figure 6 Design of erosion control at National Road NR.01B in phongsali province, laos KM90+625

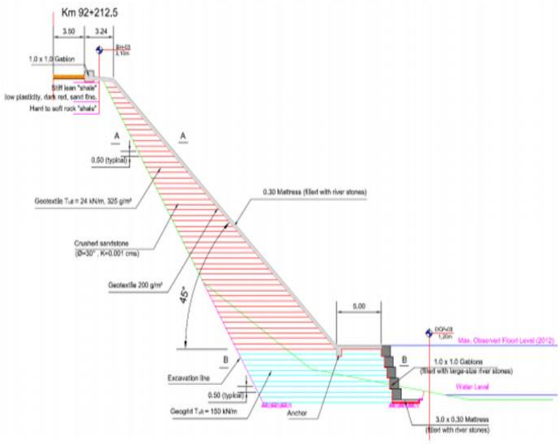

Figure 7 Design of erosion control at National Road NR.01B in Phongsali Province, Laos KM92+125

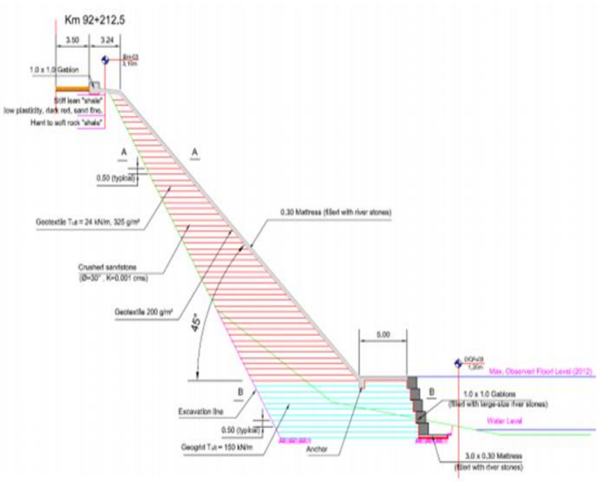

Figure 8 Design of erosion control at National RoadNR.01B in Phongsali Province, Laos KM92+212.5

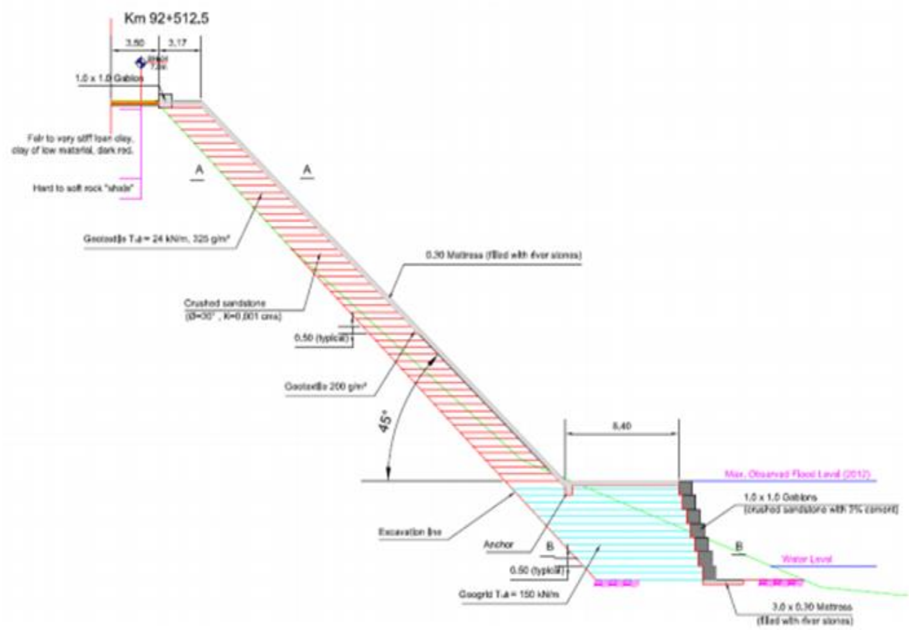

Figure 9 Design of erosion control at National RoadNR.01B in Phongsali Province, Laos KM92+512.5

Table 5 Soil models and parameters of slope mitigation along National Road 1B (NR 1B) in Laos PDR

Material	Depth (m)	Model	γ_{sat} (kN/m^3)	$2kx=ky$ (m/day)	c' (kPa)	Φ' (°)
Subsoil Weathered shale		MCM	22	0.0004	120	60
Compacted sandstones		MCM	22	0.004	30	31

3. FINITE ELEMENT ANALYSIS BY PLAXIS FEM 2D AND SLIDE PROGRAMS

PLAXIS FEM 2D analysis was used to predict the settlement of flood protection barriers with the new height extension and also utilized to predict the factor of safety for each design at different cases for both flood protection and erosion control structures.

SLIDE Limit Equilibrium software was also utilized to predict the values of factor of safety by using Simplified Bishop, Janbu and Spencer methods at different cases for both flood protection and erosion control structure using the same soil and support parameters as those used in PLAXIS FEM 2D software.

3.1 SETTLEMENT PREDICTION BY PLAXIS FEM 2D FOR FLOOD BARRIERS WITH ADDED HEIGHTS

3.1.1 Hi-Tech Industrial Estate

Hi-Tech flood protection was designed with 2.4 m height above the ground surface with an extra 1 m height berm was constructed in front of the waterside toe of the main embankment as shown in Figure 1. After major flood crisis in year 2011, Hi-Tech Industrial Estate had raised the height of the flood barrier up to 4 m and installed geocell on the water side slope. Groundwater level was assumed at 2 m depth from the ground surface. For settlement prediction by PLAXIS FEM 2D program, there were four points of interest which was at the middle of new section, water side toe, land side toe and at the middle of existing crest. The predicted 15 years (5470 days) settlement at middle of new section, water side toe, land side toe and at the middle of existing crest were 1180, 870, 410 and 1120 mm, respectively, as shown in Figure 10.

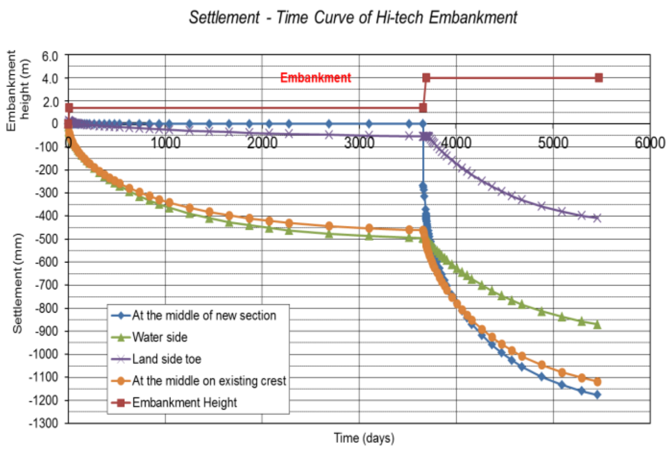

Figure 10 Graph of settlement-time curve of Hi-Tech Industrial Estate improved flood protection embankment

3.1.2 Asian Institute of Technology (AIT)

The existing AIT embankment was designed with 1 m height above ground level as shown in Figure 4. After the major flood crisis in year 2011, AIT has designed new flood protection barrier with height raised up to 2.7 m above the ground level. Groundwater was assumed at 2m depth from the ground surface. For settlement prediction by PLAXIS FEM 2D program, there were four points of interest which was at middle of new section, water side toe, land side toe and at the middle of existing crest. The predicted 15 years (5470 days) settlement at middle of new section, water side toe, land side toe and at the middle of existing crest were 443,241, 251 and 437 mm, respectively, as shown in Figure 11.

3.2 FACTOR OF SAFETY FOR FLOOD PROTECTION DIKES

The prediction of the factor of safety for each design considered 2 cases, namely: 2 m depth of ground water table and flooding with seepage case.

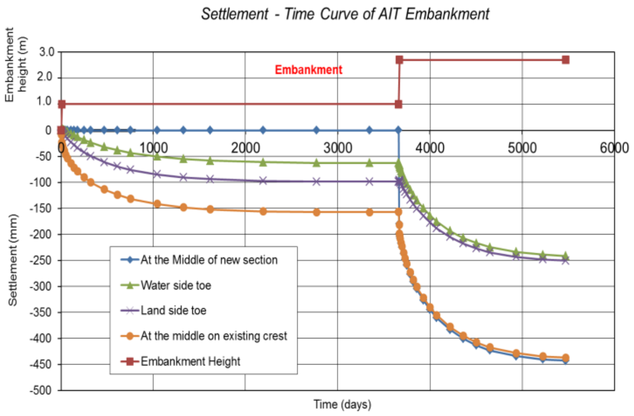

Figure 11 Graph of settlement-time curve of AIT embankment

3.2.1 Case 1 - 2 m depth of groundwater table

The results in the case of 2 m depth of groundwater table are shown in Table 6. The results show that the values of the Factor of Safety for the optimum flood protection dike design simulated by both PLAXIS FEM 2D and SLIDE softwares at the Navanakorn Industrial Estate were FS=2.743 and FS=3.295 as shown in Figures 12 and 13, respectively.

Table 6 Values of factor of safety from PLAXIS and SLIDE of flood protection dike with 2 m depth of groundwater at Navanakorn

Design	PLAXIS FEM 2D	SLIDE Software
Hi-Tech	1.37	Bishop = 1.51
		Janbu = 1.43
		Spencer = 1.50
Bang Pa-In	1.79	Bishop = 2.16
		Janbu = 1.96
		Spencer = 2.16
Navanakorn	1.63	Bishop = 2.16
		Janbu = 2.10
		Spencer = 2.19
AIT	1.62	Bishop = 1.96
		Janbu = 1.74
		Spencer =1.96

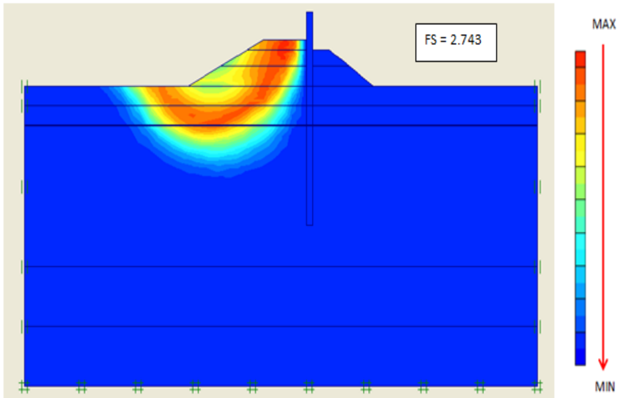

Figure 12 Total displacement and factor of safety from PLAXIS 2D analyses of Navanakorn flood control dike with 2 m depth of groundwater table

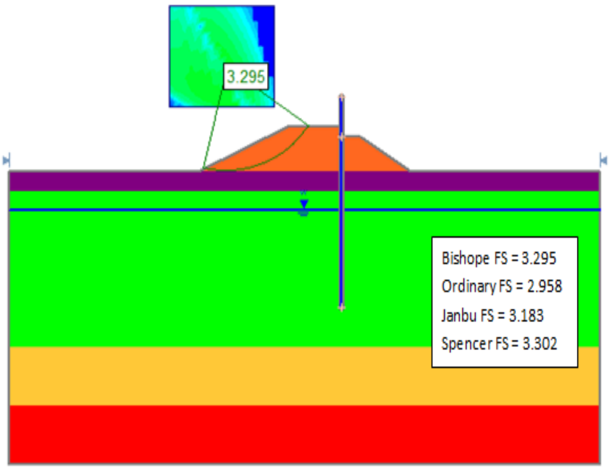

Figure 13 Values of factor safety from SLIDE software at Navanakorn embankment with 2 m depth of groundwater table

3.2.2 Case 2 – Flooding with seepage

The stability results in the case of flooding with seepage are shown in Table 7. The results show that the optimum flood protection barriers design in case of flooding with seepage simulated by both PLAXIS FEM 2D and SLIDE software at Bang Pa-In Industrial Estate design with FS=1.791 and 2.164 as shown in Figure 14 and 15, respectively.

Table 7 Values of factor of safety from PLAXIS and SLIDE of flood protection dike with flooding and seepage at Bang Pa-In

Design	PLAXIS FEM 2D	SLIDE Software
Hi-Tech	1.37	Bishop = 1.51
		Janbu = 1.43
		Spencer = 1.50
Bang Pa-In	1.79	Bishop = 2.16
		Janbu = 1.96
		Spencer = 2.16
Navanakorn	1.63	Bishop = 2.16
		Janbu = 2.10
		Spencer = 2.19
AIT	1.62	Bishop = 1.96
		Janbu = 1.74
		Spencer =1.96

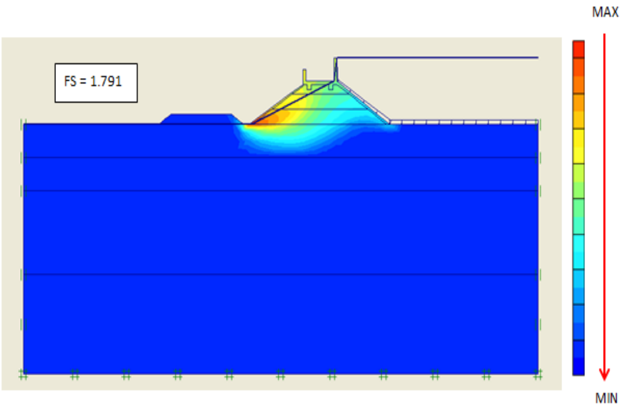

Figure 14 Total displacement and factor safety from PLAXIS FEM 2D at Bang Pa-In embankment with flooding and seepage

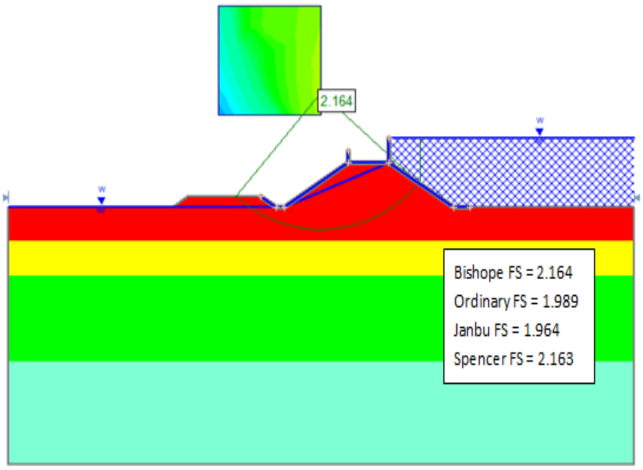

Figure 15 Values of factor safety from SLIDE software at Bang Pa-In embankment with flooding and seepage

3.3 FACTOR OF SAFETY FOR EROSION CONTROL STRUCTURES

3.3.1 Case 1 – Low water level

The stability analyses results in the case of low water level are shown in Table 8. The analyses of river bank mitigation protection schemes in cases of low water level utilizing both PLAXIS FEM 2D and SLIDE software for this case showed that at station KM90+625 with highest FS as shown in Figures 16 and 17, respectively.

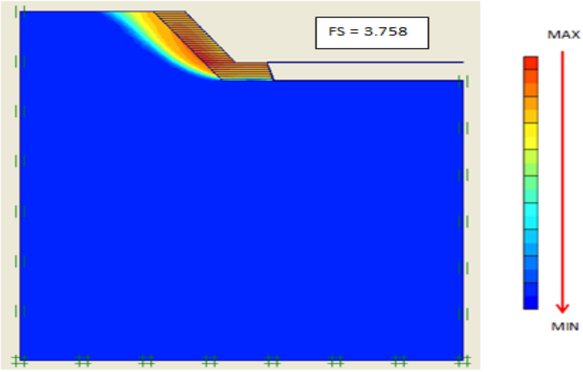

Figure 16 Factor of safety from PLAXIS FEM 2D of riverbank erosion control in Laos (KM90+625) with low water level

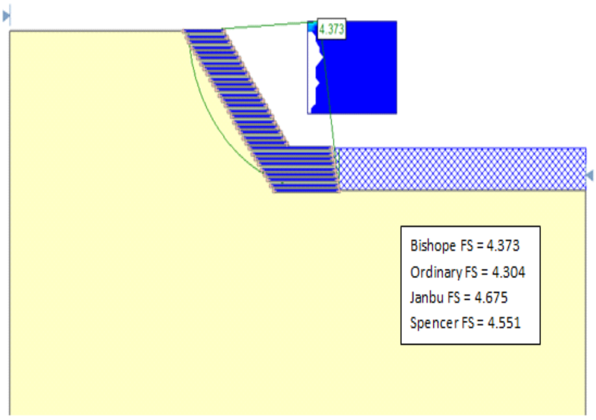

Figure 17 Factor safety from SLIDE software of riverbank erosion control in Laos (KM90+625) with low water level

Table 8 Values of factor of safety from PLAXIS and SLIDE of erosion control structures with low water level

Design	PLAXIS FEM 2D	Slide Software
KM90+625	3.76	Bishop = 4.37 Janbu = 4.68 Spencer = 4.55
KM92+125	3.01	Bishop = 3.63 Janbu = 3.44 Spencer = 3.58
KM92+212.5	2.96	Bishop = 3.09 Janbu = 2.94 Spencer = 3.08
KM92+512.5	2.99	Bishop = 3.69 Janbu = 3.46 Spencer = 3.63

3.3.2 Case 2 – High water level

The stability analyses results in the cases of high water level which was around 2/3 of the structure's height are shown in Table 9. The analyses of river bank mitigation protection schemes in cases of high level utilizing both PLAXIS FEM 2D and SLIDE softwares for this case show that at station KM90+625 yielded highest FS as shown in Figures 18 to 19, respectively.

Table 9 Values of factor of safety from PLAXIS and SLIDE of erosion control structures with high water level

Design	PLAXIS FEM 2D	Slide Software
KM90+625	4.32	Bishop = 4.72 Janbu = 4.81 Spencer = 4.84
KM92+125	3.29	Bishop = 3.89 Janbu = 3.63 Spencer = 3.75
KM92+212.5	3.26	Bishop = 3.39 Janbu = 3.24 Spencer = 3.31
KM92+512.5	3.30	Bishop = 3.93 Janbu = 3.64 Spencer = 3.80

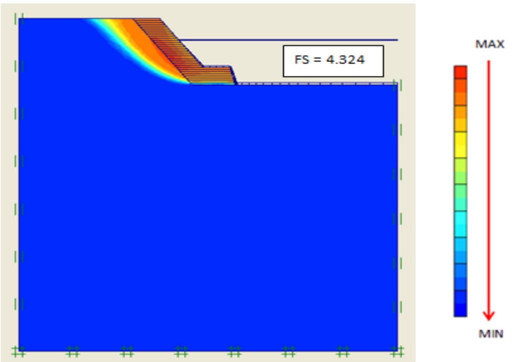

Figure 18 Factor safety from PLAXIS FEM 2D of Lao riverbank (KM90+625) with high water level

4. CONCLUSIONS

Bangkok flood crisis occurred in 2011, which caused devastating damage to economy and life. During that time, many flood protection dikes around Bangkok areas were overtopped by high flood waters. After the crisis, new and improved flood protection dikes have been redesigned in order to improve its protection against future flooding.

For the case of flood protection structures, the settlement of flood protection barriers with added height were simulated by PLAXIS FEM 2D. The 15 years predicted settlements are higher for Hi-tech Industrial estate design compared to AIT design due to higher added height of the structure of the former than the later.. Moreover, slope stability analyses of each flood and erosion protection barrier were simulated by PLAXIS FEM 2D and Limit Equilibrium SLIDE softwares. The results show that in case of 2 m depth of groundwater table, the Navanakorn Industrial Estate design has highest FS because lower height of the flood control dike. Moreover, this design was combined with RC sheetpiles compared to some other design. And for the case of flooding with seepage, Bang Pa-In Industrial Estate has improved stability because the embankment surface was installed with concrete slab.

In the same period, unusually heavy monsoon rains, exacerbated by tropical storms, have caused widespread flooding in more than 60 percent of northern Laos PDR and caused slope failures along National Road 1B (NR 1B) in Phongsali Province which required mitigation measures. The stability predictions for the erosion control structures along National Road 1B (NR 1B) were analysed in 2 cases, namely: low and high water levels. For both cases of low and high water levels, the highest values of factor of safety (FS) occurred at KM90+625 due to lower height and smaller slope fill.

From all analyses, the factor of safety from SLIDE software always show higher values compared to PLAXIS FEM 2D due to the over predicted of limit equilibrium method. From all the computed results, PLAXIS FEM 2D has higher accuracy compared to SLIDE limit equilibrium software.

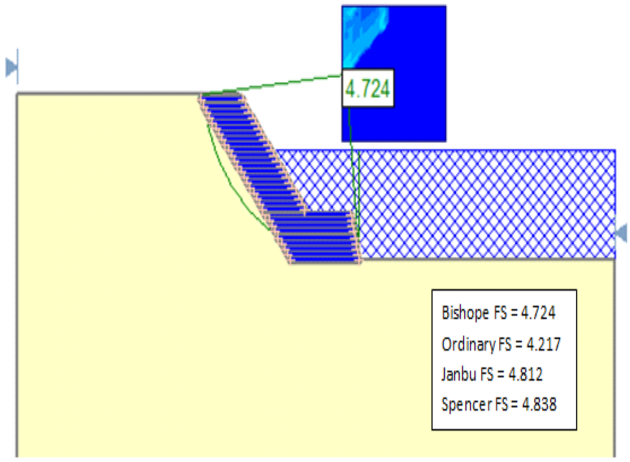

Figure 19 Factor safety from SLIDE software of riverbank erosion control in Laos (KM90+625) with high water level

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