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Research Paper

Mitigations of flooding and soil erosions Geo-Disasters in Thailand and Laos due to climate change: From Mountains to Lowlands

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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, to name a few. The same phenomenon also occurred in neighboring Laos PDR which caused unusually heavy rains and widespread river flooding. Consequently, riverbank erosions accompanied by slope failures occurred at Xedon River in Pakse, Southern Laos due to saturation caused by high water levels accompanied by high velocity flow of the flooded river. To evaluate the stability of these mitigation structures, finite element and limit equilibrium methods were utilized. PLAXIS 2D software was used to analyze the slope protection schemes at low and high water levels incorporating the various supporting and reinforcing materials. Moreover, the PLAXIS 2D software was also utilized to predict the vertical deformations of improved flood control dikes with increased embankment height at different cases of flood water levels. In addition, the SLIDE software was used to predict the factor of safety by using limit equilibrium method for the various riverbank erosion protection structures. Furthermore, RESSA software was utilized to evaluate the slope stability of the erosion protection structures with geosynthetic reinforcements of Xedon riverbank in Pakse combined with gabions and mattresses. Laos PDR is mountainous with high elevations.

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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-lying area. The common cause of flooding is due to unusually heavy rainfall which also increases the water flow of rivers. To prevent from flooding problem, a dike or embankment is usually constructed along the boundaries of the protected areas to prevent overflowing of flood waters. The flood water levels should be considered for the design of the dike and which ground level is considered in the setting of flood levels. Thus, the dike level should be higher compared to the surrounding areas. In some cases, concrete retaining wall is installed to increase the height of the structure (Department of Public Works and Highways Japan International Cooperation Agency, 2010). For flood protection structures, 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 provide a protective cover to the ground against surface erosion with lower cost but less effective if compared to geosynthetics. Moreover, Tanchaisawat et al. (2014) and Artidteang et al. (2016) have demonstrated that the combinations of Ruzi grass and Limited Life Geosynthetics (LLGs) made from Water Hyacinth can be most effective in controlling soil surface erosion.

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 should have gone to Taiwan and Japan. Subsequently, water was released from the full dam reservoirs in Northern Thailand which overflowed the rivers. The flood waters 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, Asian Institute of Technology, etc. Consequently, reconstructions were done in the flood protection dikes with different improvement techniques to prevent flooding in the near future.

At the same time, unusually heavy rains due to the abnormal storms caused environmental geo-disasters in neighboring country of Laos PDR (Disaster Relief Emergency Fund Retrieved, 2013). Consequently, slope failures and severe riverbank erosions occurred along Xedon River (a tributary of Mekong River) in Pakse, Southern, Laos PDR. Compacted silty sand fill reinforced with geosynthetics combined with gabions and mattresses were utilized for improvement of slope stability and erosion protection at the riverbanks (Bergado et al., 2016).

The objective of this paper is to evaluate the various improvements of flood control dikes and erosion protection schemes using different techniques (geosynthetics, vegetations, gabions and mattresses) and evaluate which design has the capability in terms of slope stability and deformations by using PLAXIS FEM 2D and SLIDE Limit Equilibrium Softwares. Some results in this paper were obtained from the previous research of Chanmee (2013).

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 comprised 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, to name a few examples. Besides the overflow, seepage of water through the flood control dikes was also observed (IEAT, 2012).

2.1 *Hi-Tech Industrial Estate*

Hi-Tech Industrial Estate is located along 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 are indicated at four points, which was at the middle of new section (1), water side toe (2), land side toe (3) and at the middle of existing crest (4) as shown in **Fig. 1**. The Industrial Estate Authority of Thailand (IEAT) suggested increasing the height of flood protection barrier from elevation +3.800 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.**

2.2 *Bang-Pa Industrial 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 was protected by flood protection barrier at +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. For settlement prediction, there were four points of interest which was at the middle of new section (1), water side toe (2), land side toe (3) and at the middle of existing crest (4). The location and dike design of Bang Pa-In Industrial Estate is shown in **Fig. 2**. The new dike uses a combination of geotextile, RC floodwall and concrete slab for erosion protection and increased stability. IEAT suggested increasing 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 1. Soil models and parameters at Hi-Tech Industrial Estate.

Material	Depth (m)	Model	γsat (kN/m^3)	2kx=ky (m/day)	c' (kPa)	Φ' (°)
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

Table 2. Soil models and parameters at BangPa-In Industrial Estate.

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

Table 3. Soil models and parameters at Navanakorn Industrial Estate.

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

Table 4. Soil models and parameters of AIT.

Material	Depth (m)	Model	γsat (kN/m^3)	2kx=ky (m/day)	c' (kPa)	Φ' (°)
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

MCM: Mohr Coulomb Model, SSM: Soft Soil Model

2.3 *Navanakorn Industrial Estate*

Navanakorn Industrial Estate is located along Phaholyothin Road, Klong Luang, Pathumthani Province. The elevation inside Navanakorn Industrial Estate is +1.400 MSL and was protected by flood protection barrier at +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 sheet piles 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, with studied behavior at the locations of middle of new section (1), water side toe (2), land side toe (3) and at the middle of existing crest (4). Soil models and parameters of Navanakorn Industrial Estate are tabulated in **Table 3.**

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 **Fig. 4** which was constructed with height of +4.700 MSL.

The general soil profile and basic soil properties at AIT were investigated by Bergado et al. (1995) and Jamsawang (2009) 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 depth, followed by the 2m thick layer of medium stiff clay and underlain by stiff clay layer which can be found down to 15m depth. Soil models and parameters of AIT site are tabulated in **Table 4.**

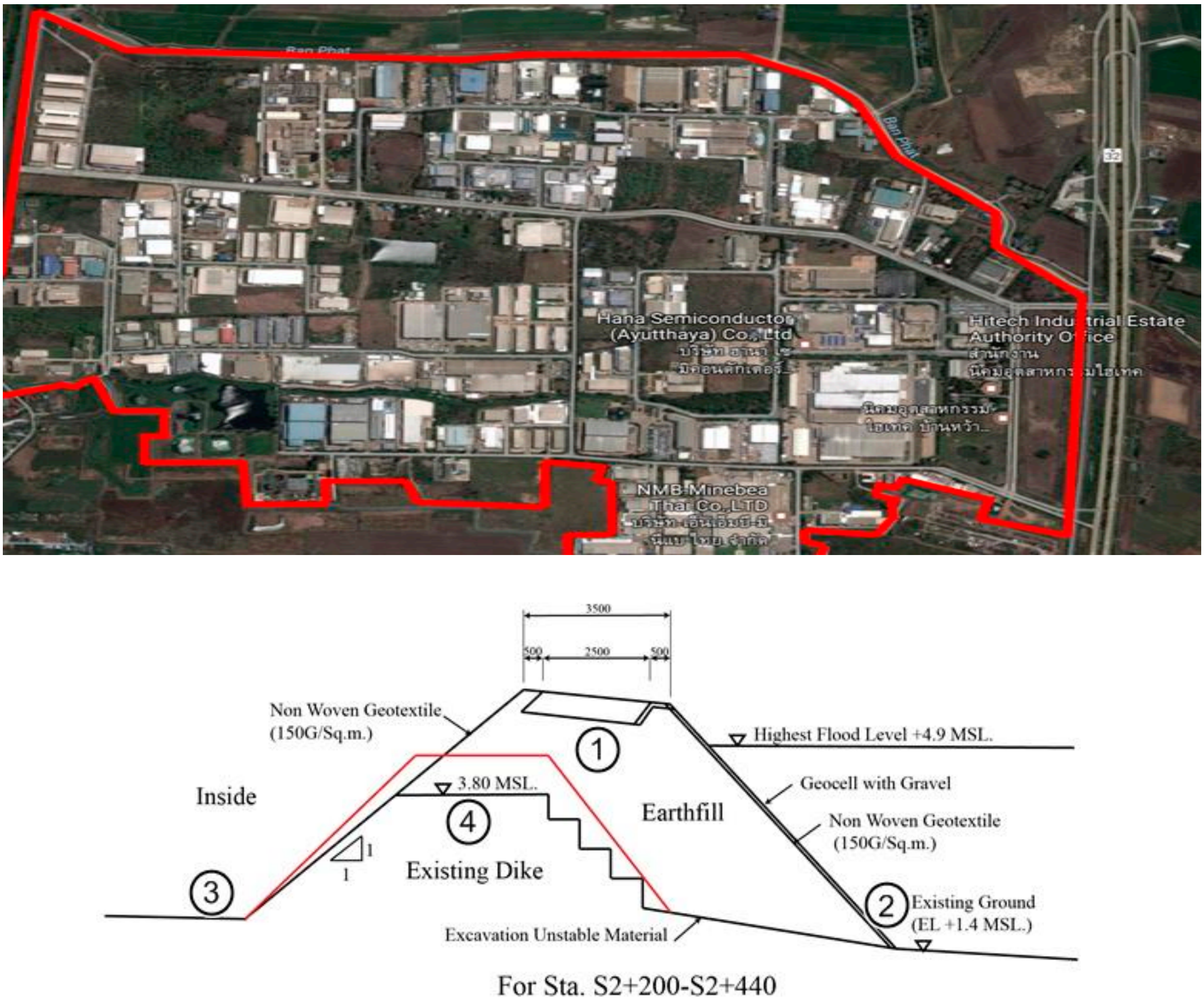


Fig. 1. Location and new dike design of Hi-Tech Industrial Estate.

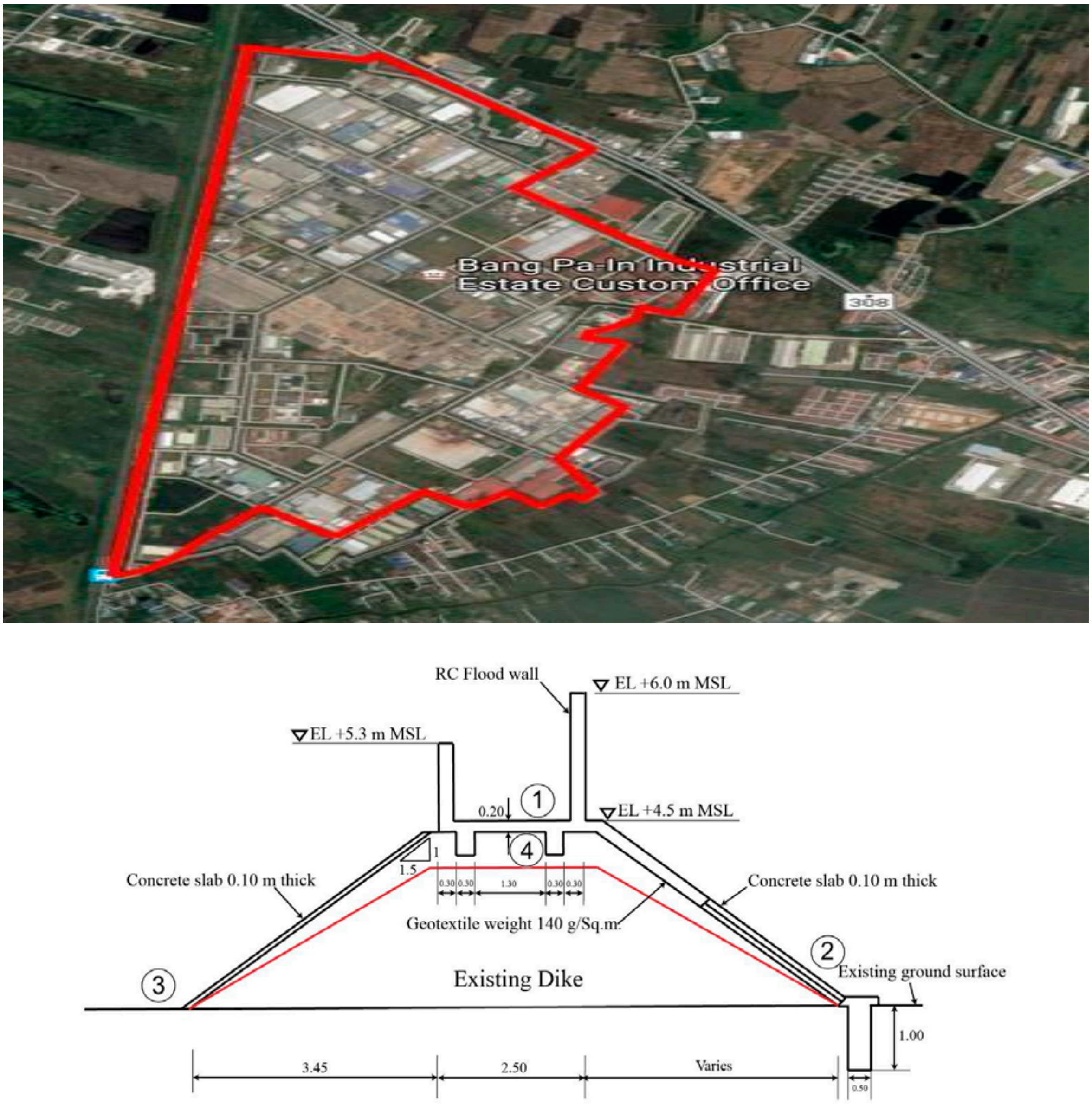


Fig. 2. Location and new dike design at Bang Pa-In Industrial Estate.

2.5 Xedon Riverbank Collapse/Erosions in Pakse, Southern Laos and their Mitigations

Pakse is the biggest city in Southern Laos along the banks of the Mekong River as shown in **Fig. 5.** Xedon River is a tributary to Mekong River in Pakse whose banks have been flooded and severely eroded for many years by heavy rainfalls due to climate change. In 2011, unusually heavy monsoon rains, exacerbated by tropical storms, have caused widespread flooding in more than 60 percent of the Laos. The monsoon rains continued, and the country endured almost continuous heavy rainfall or some ten weeks (Disaster Relief Emergency Fund, 2013). At the end of the wet season, the riverbank soil has maximum moisture content at almost saturated conditions which increases its weight with high pore-water pressures that reduces its shear strength. Consequently, the riverbank soils weaken and more prone to erosion and slippage, particularly, when combined with rapidly receding river water levels in a sudden drawdown condition as well as high water velocity. Most riverbank erosion occurs at the outer curve of a meandering river as illustrated in **Figs. 6 and 7.**

The mitigation measures consist of geosynthetic reinforcements (T_{ult} = 150 kN/m) at 1.0 m vertical spacing of compacted silty sand fill combined with surface mattresses and rock filled gabions in the lower sections for erosion protection. The erosion protection scheme at Xedon River is shown in **Fig. 8a, b** with factor safety (FS) of 1.25 at sudden drawdown condition at 0.1g earthquake loading.

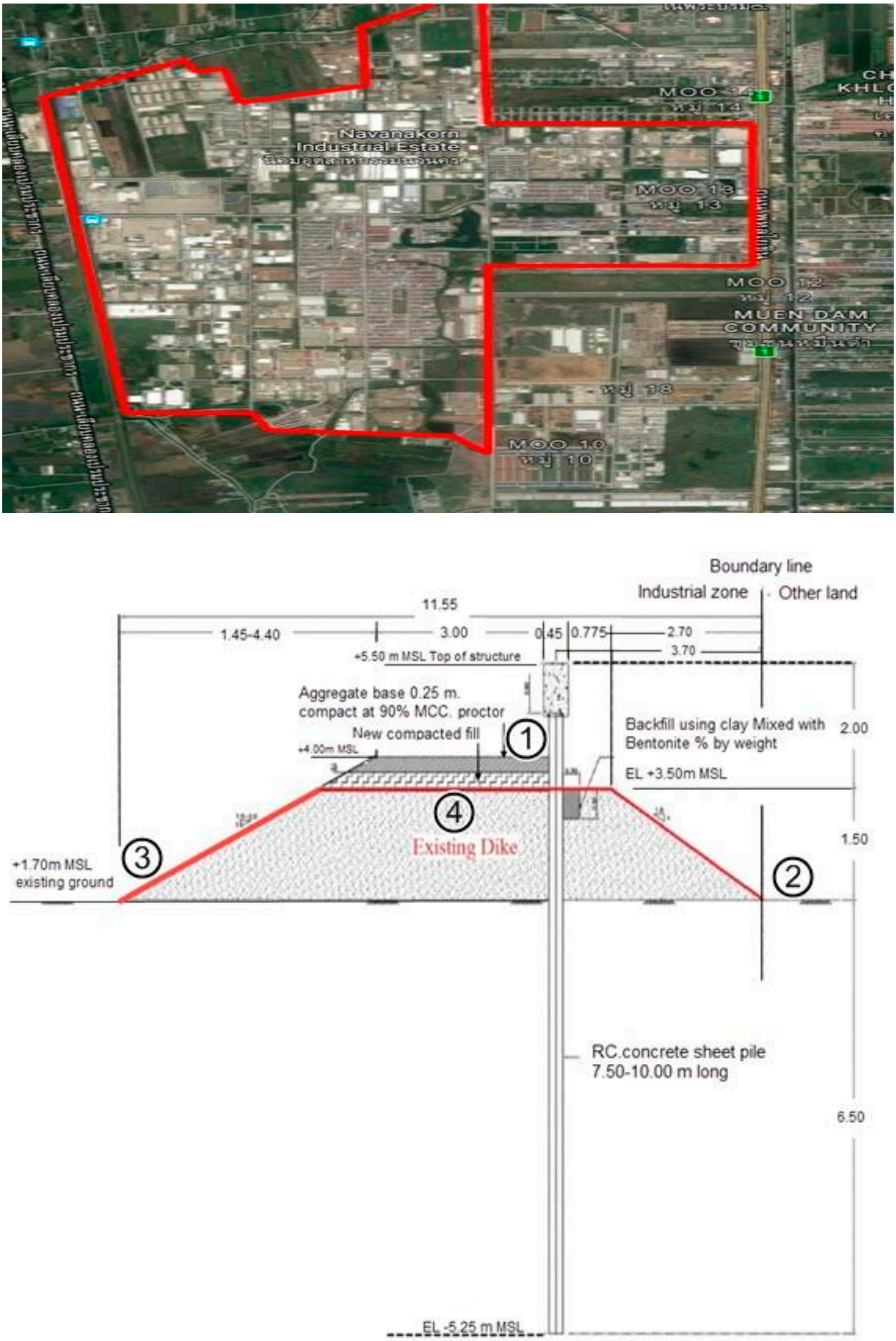


Fig. 3. Location and new dike design at Navanakorn Industrial Estate.

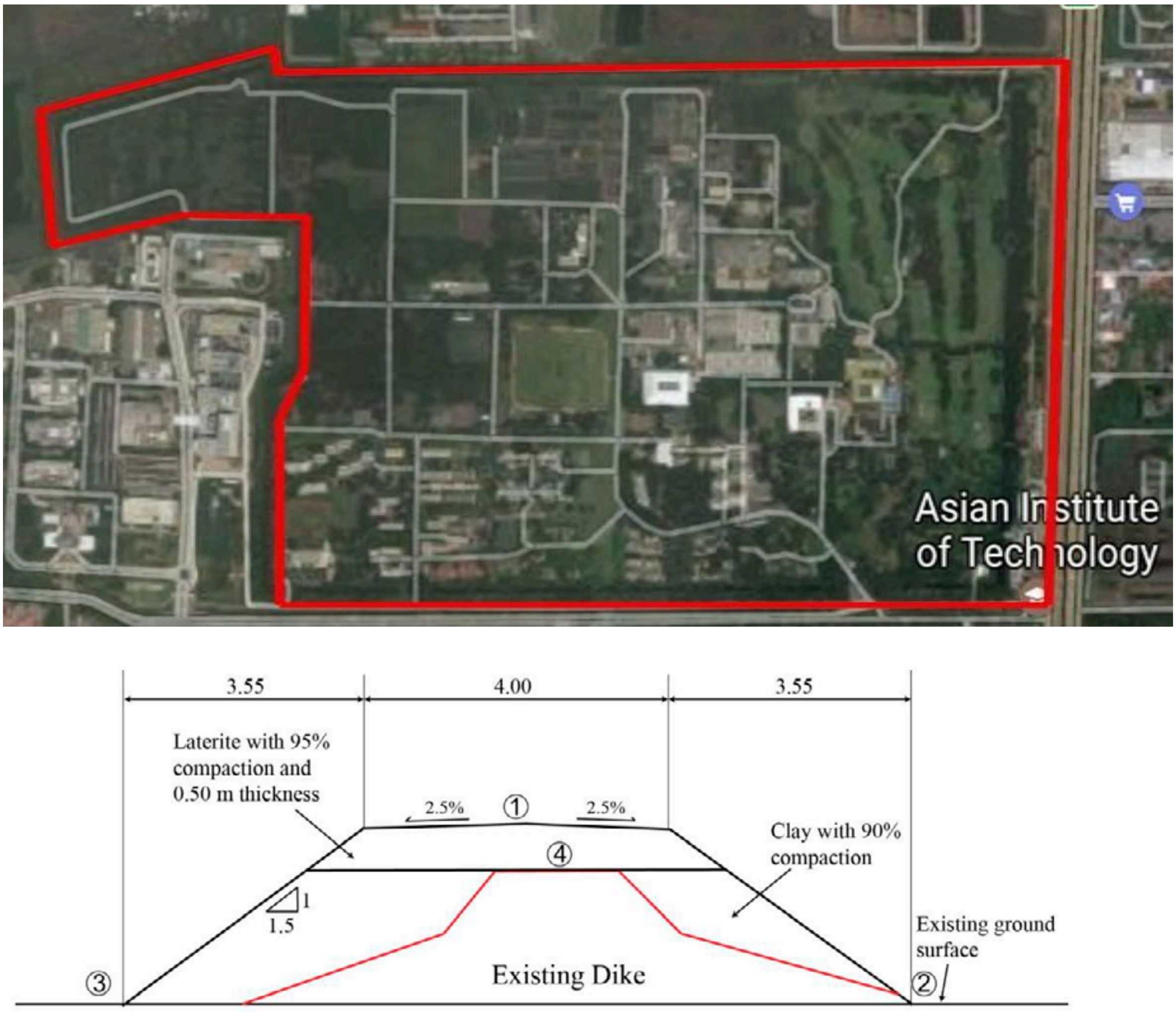


Fig. 4. Location and new dike design of Asian Institute of Technology (AIT).

3. Additional slope stability analysis for erosion protection structure at Xedon riverbanks

3.1 Slope stability of unreinforced slopes using RESSA

The riverbank slope at the Xedon River was generally grouped into 3 classifications, namely: Typical Sections 1 to 3. Typical Sections 3 and 1 are featured in **Figures 9 and 10,** respectively. The stability analyses results in the case of unreinforced slopes using RESSA software. RESSA software is commercial software that can be used to analyze the stability of both unreinforced and reinforced slopes. For sudden drawdown condition with earthquake loading of 0.1g and surcharge of 10 kPa, the factor of safety (FS) values were obtained as 1.1 and 0.80, corresponding to Typical Sections 3 and 1 in **Figs. 9a and 10a,** respectively. The lowest values of the factor of safety were obtained at infinite failure condition where the failure planes are almost parallel to the slope surface. These values of the factor of safety are below the safe criteria of 1.2 at sudden drawdown condition with 0.1g earthquake loading.

3.2 Slope stability of reinforced slopes using RESSA

The stability analyses results in the case of reinforced slopes using RESSA software are indicated in **Figures 9b and 10b** corresponding to Typical Sections 3 and 1, respectively. The reinforcements consisted of 3 m long PEC 150 geotextiles with T_{ult} of 150 kPa per m wide at 1.0 m vertical spacing. The values of the factor of safety were 1.2 and 2.0, respectively, at sudden drawdown condition with 0.1g earthquake and 10 kPa surcharge loadings. The short geotextile reinforcements were mainly used to prevent the infinite slope failures.

4. Finite element analysis by Plaxis FEM 2D and SLIDE programs at Hi-Tech and AIT dikes

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

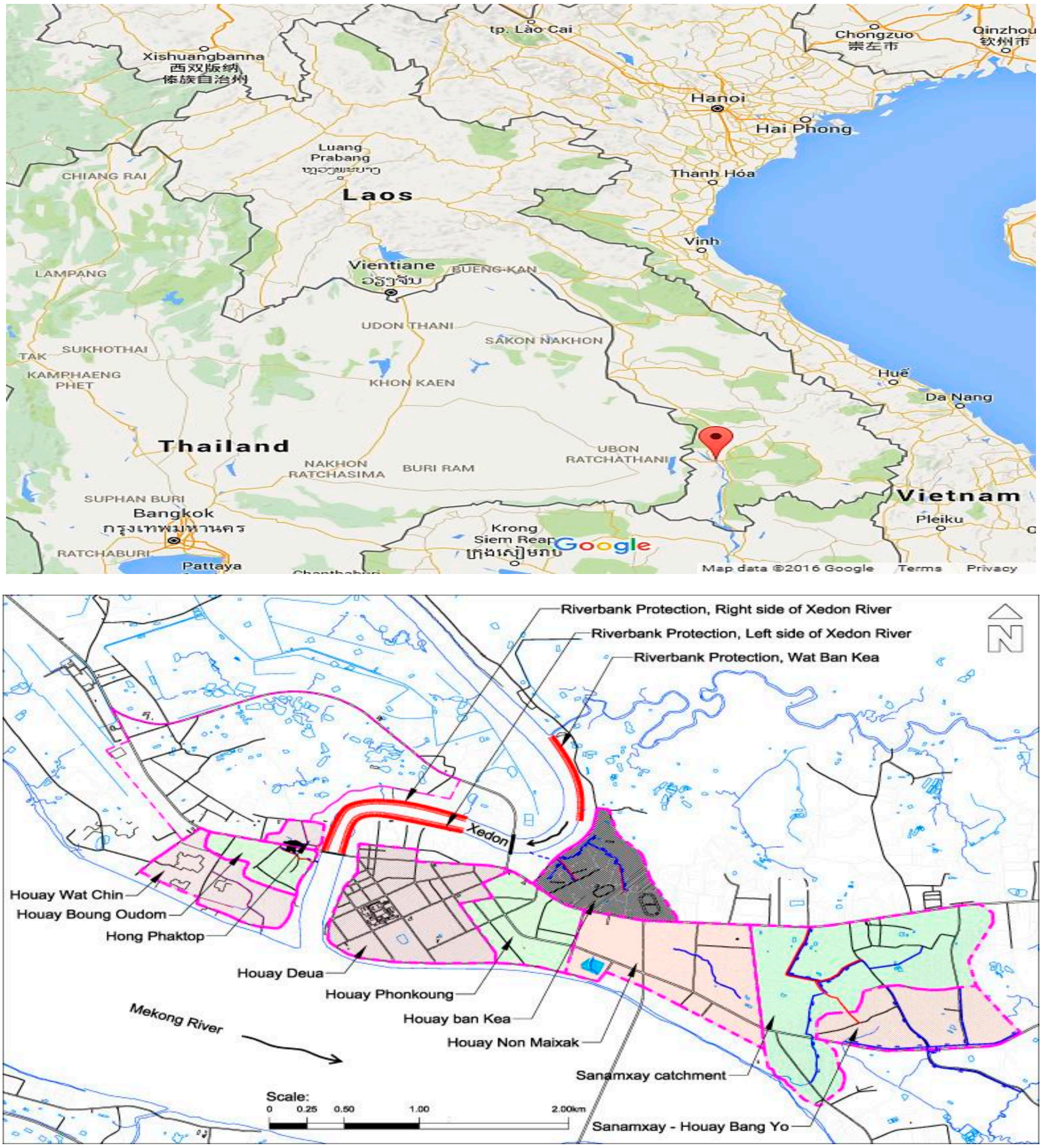


Fig. 5. Site location of Xedon River in Pakse, Southern Laos PDR.

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 u sing the same soil and support parameters as those used in PLAXIS FEM 2D software.

4.1 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 **Fig. 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 (1), water side toe (2), land side toe (3) and at the middle of existing crest (4). The predicted 15 years)5470 days(settlements at middle of new section, water side toe, land side toe and at the middle of existing crest were 1180, 870, 410 and1120 mm, respectively, as shown in **Fig. 11**.

Fig. 6. Photos of Xedon Riverbank erosion at the outer curve.

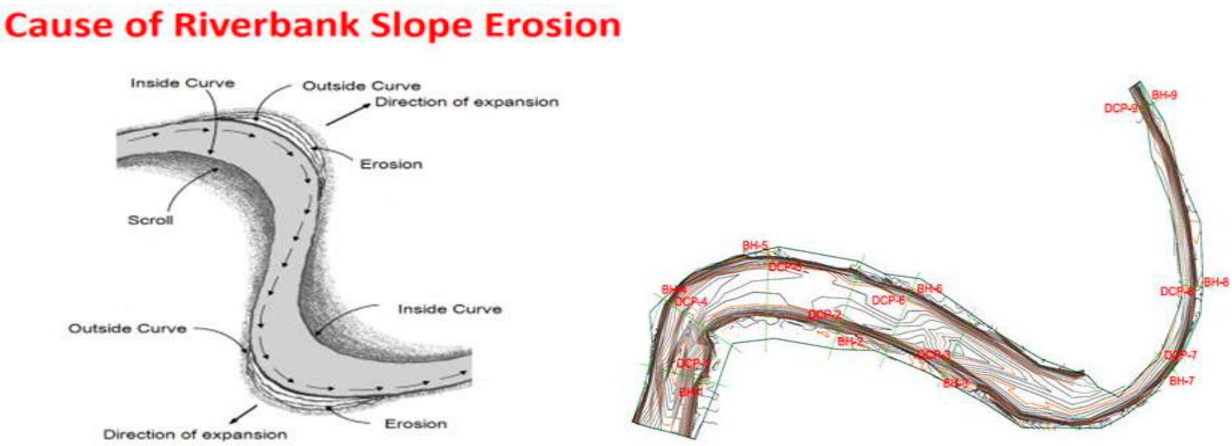
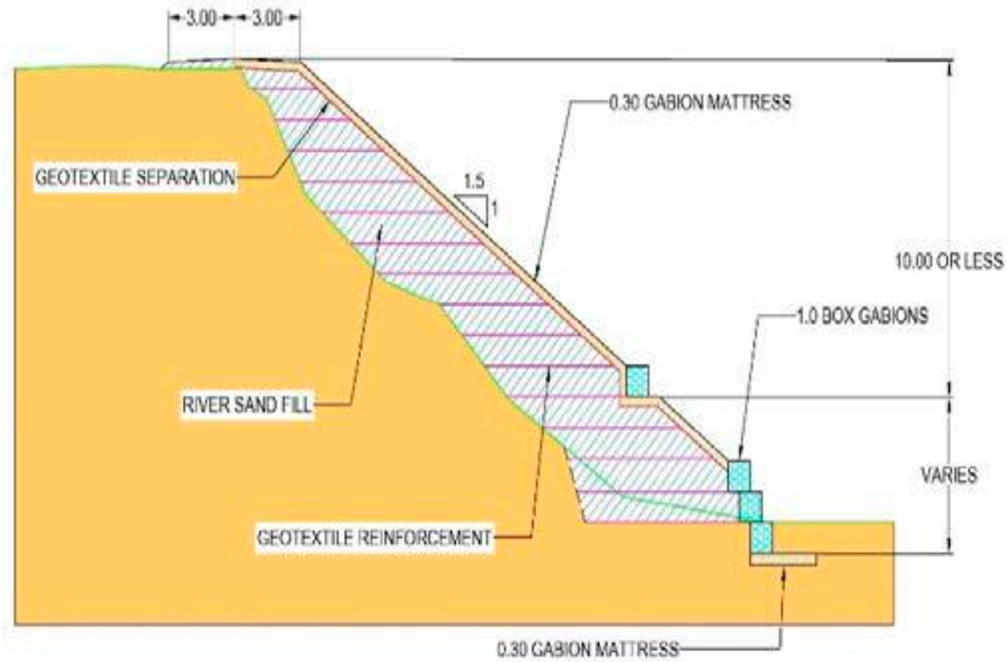
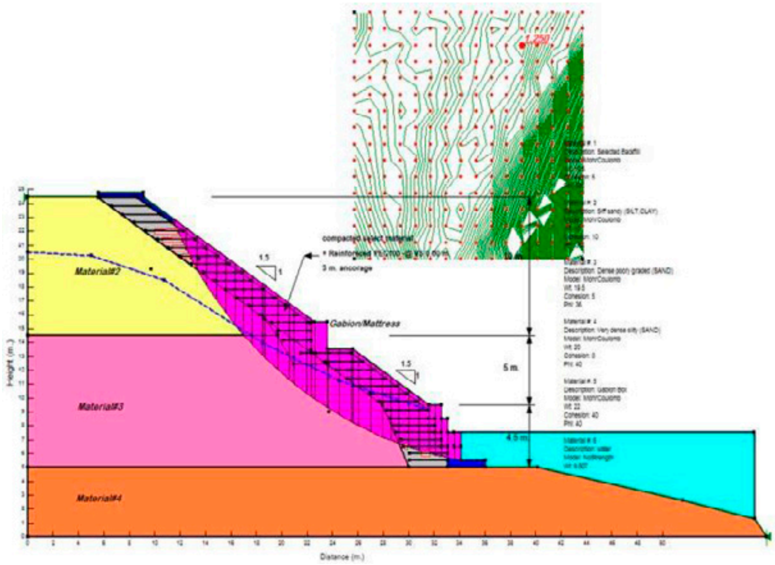


Fig. 7. Causes and characteristics of riverbank erosions at Xedon River in Pakse, Southern Laos PDR.



(a(



(b)
Fig. 8. Erosion protection scheme at the Xedon Riverbank with factor of safety (FS) of 1.25 (SLIDE software).

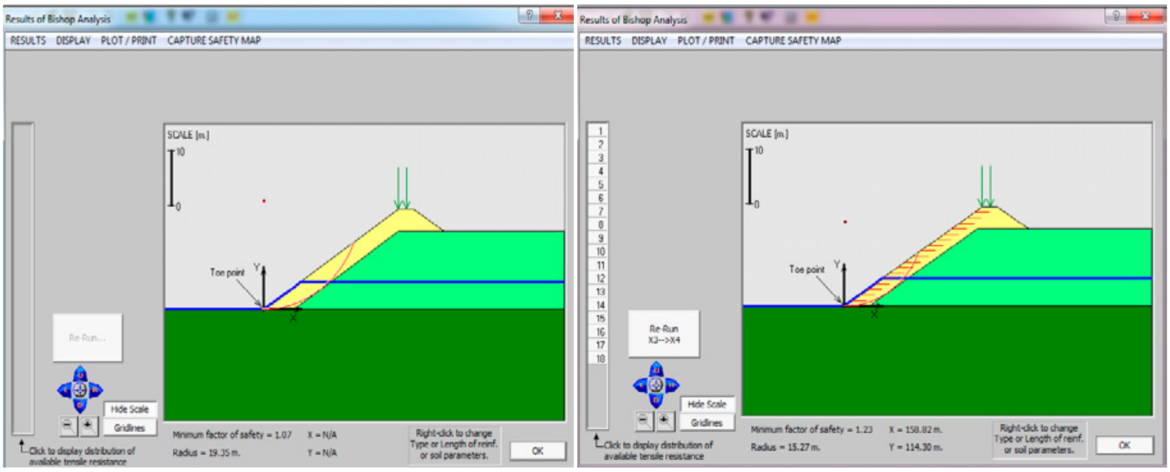


Fig. 9. Slope stability analyses of unreinforced (FS=1.1) and reinforced (FS=1.2) slopes using 3m long PEC150 geotextile reinforcements at 1.0 vertical spacing with 0.1g earthquake loading and sudden drawdown condition for Typical Section 3, Xedon Riverbank (RESSA).

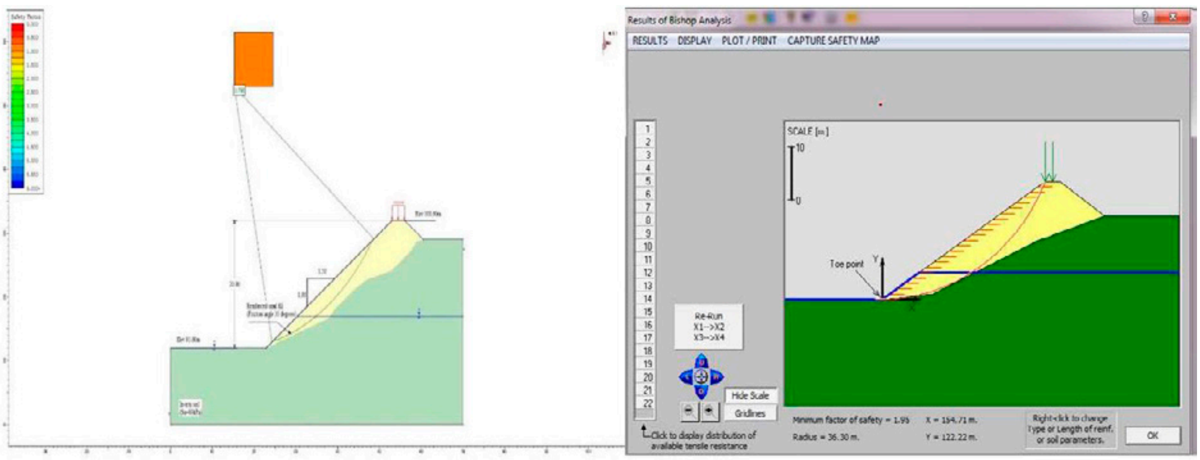


Fig. 10. Slope stability analyses of unreinforced infinite (FS=0.8) and reinforced (FS=2) slopes using PEC150 geotextile reinforcement at 1.0 m vertical spacing with 0.1g earthquake loading and sudden drawdown condition for Typical Section 1, Xedon Riverbank (RESSA).

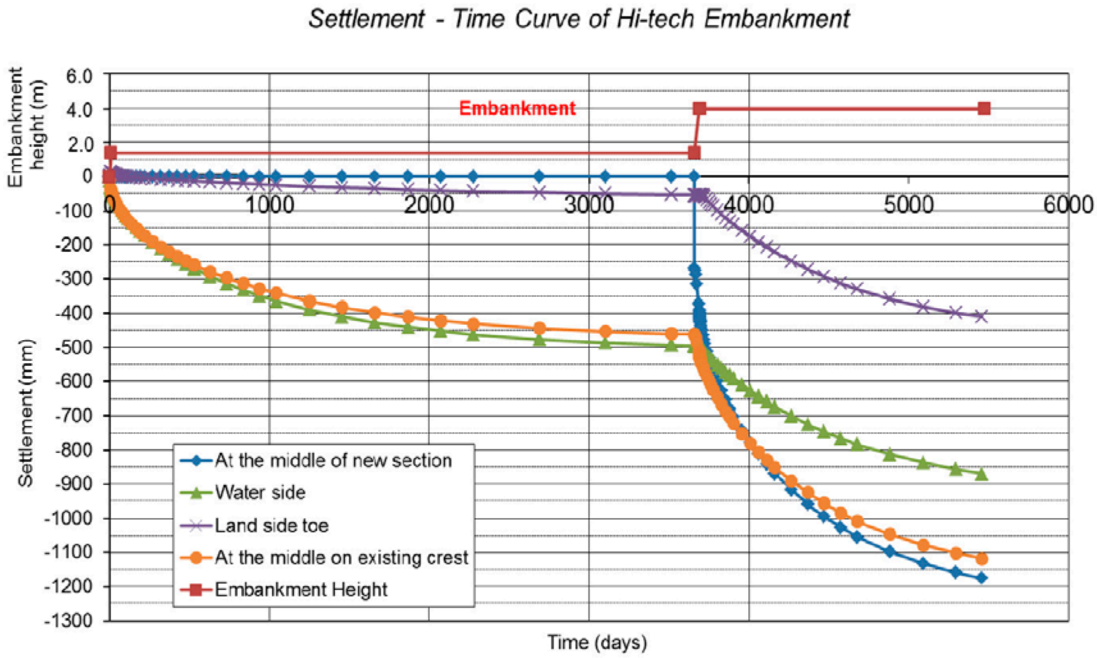


Fig. 11. Settlement-time curves of Hi-Tech Industrial Estate improved flood protection embankment (refer to numbered locations in Fig. 1) using FEM 2D software.

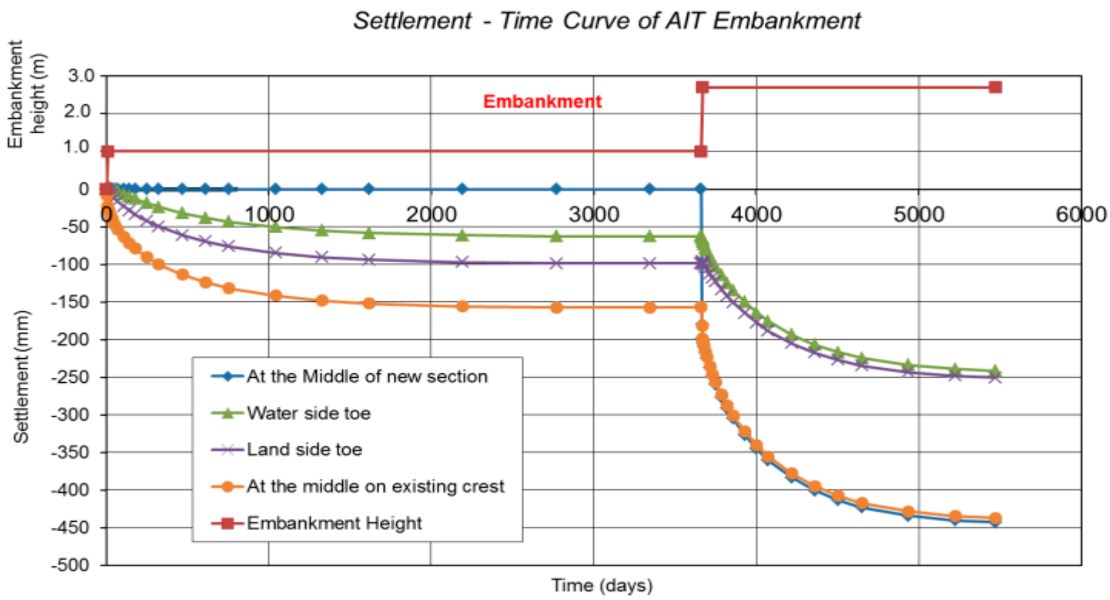


Fig. 12. Settlement-time curve of AIT embankment (refer to numbered locations in Fig. 4) using FEM 2D software.

4.2 Asian Institute of Technology (AIT)

The existing AIT embankment was designed with 1 m height above ground level as shown in **Fig**. **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 (1), water side toe (2), land side toe (3) and at the middle of existing crest (4). The predicted 15 years (5470 days) settlements 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 **Fig**. **12**.

5. Values of factor of safety for flood control dikes at Navanakorn and Bang Pa-in industrial estates

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

5.1 Case 1 – Two-meter depth of groundwater table

The results in the case of 2 m depth of groundwater table are shown in **Table 5**. 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 **Figs**. **13 and 14**, respectively.

5.2 Case 2 –Flooding with seepage

The stability results in the case of flooding with seepage are shown in **Table 6** .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 **Figs. 15 and 16,** respectively.

Table 5. Values of factor of safety from PLAXIS and SLIDE of flood protection dike with 2 m depth of groundwater at Navanakorn Industrial Estate.

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

Table 6. Values of factor of safety from PLAXIS and SLIDE of flood protection dike with flooding and seepage at Bang Pa-In Industrial Estate.

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

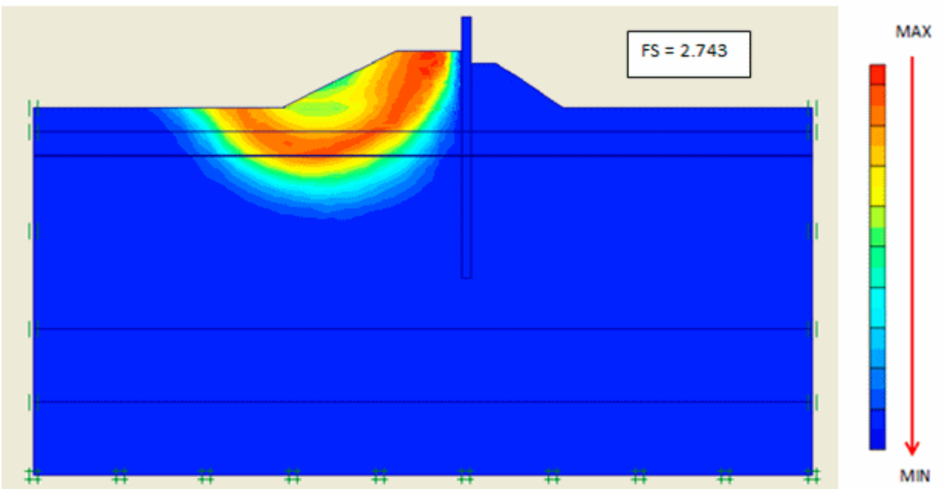


Fig. 13. Total displacements and factor of safety from FEM PLAXIS 2D software of Navanakorn flood control dike with 2 m depth of groundwater table.

6. Conclusions

Bangkok flood crisis occurred in 2011, which caused devastating damage to economy and life. During that time, many flood protection dikes around the Central Plains of Thailand 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

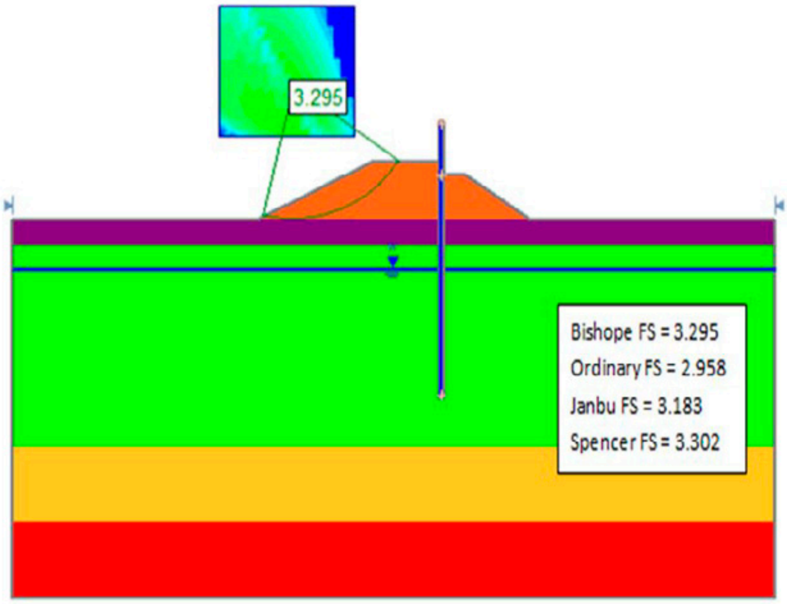


Fig. 14. Values of factor safety from SLIDE software at Navanakorn flood control dike with 2 m depth of groundwater table.

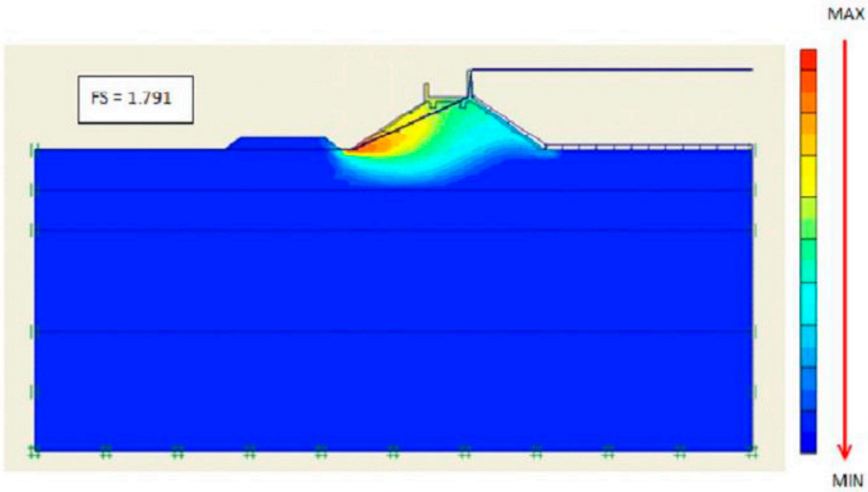


Fig. 15. Total displacement and factor safety from PLAXIS FEM 2D software at Bang Pa-In flood control dike with flooding and seepage.

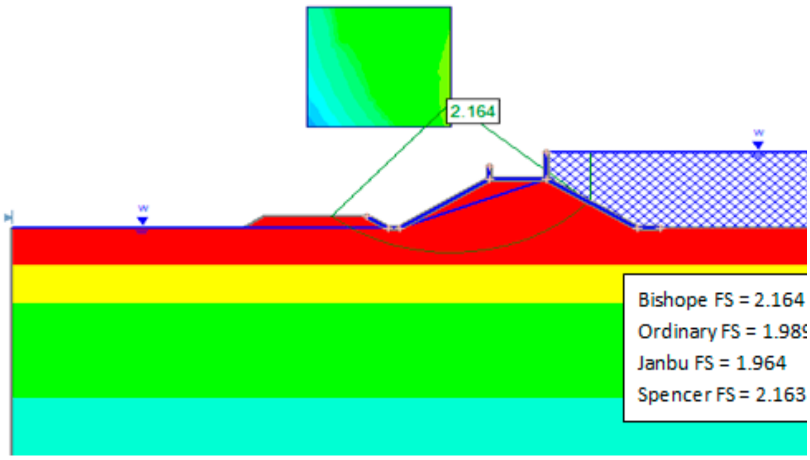


Fig. 16. Values of factor safety from SLIDE software at Bang Pa-In flood control dike with flooding and seepage.

added height of the flood protection 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 of lower height of the flood control dike. Moreover, this design was combined with Reinforced Concrete (RC) sheet piles 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. The factor of safety values from SLIDE software demonstrated higher values compared to PLAXIS FEM 2D due to the over predictions of limit equilibrium method of the former.

In the same period, unusually heavy monsoon rains, exacerbated by tropical storms, have caused widespread flooding in neighboring country of Laos PDR and caused slope collapse and riverbank erosions of Xedon River in Pakse, Southern Laos. The mitigations for riverbank erosion protection consisted of geotextile reinforcements combined with mattresses and gabions. In addition, RESSA software was utilized to analyze the stability of geotextile reinforced as well as unreinforced erosion control schemes. In contrast to the lowlands of the Central Plain of Thailand where the soil deposits are dominated by soft Bangkok clay which is highly compressible and weak, Laos PDR is mountainous with higher elevations. In Laos PDR, the problem is mostly dominated by soil erosions along riverbanks.

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Symbols and abbreviations

MSL	Mean Sea Level
MCM	Mohr Coulomb Model
SSM	Soft Soil Model
RC	Reinforced Concrete
PDR	People's Democratic Republic