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Geotechnical investigation of the 2017 earth-filled embankment failures in Thailand

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Abstract

This present study was to investigate the potential geotechnical causes of the failures of two earth-filled embankments occurred in 2017 in Thailand. The Huai Sai Kamin embankment dam was the first failure that occurred on July 28th. The Nong Sano reservoir was the second failure that occurred on October 18th. Geological, geotechnical and hydrological data were collected and analyzed together meteorological data. In addition, site visits were performed to collect soil samples for testing. The results show that the embankment of the Huai Sai Kamin dam was well compacted of clayey sand (SC) over an alluvial soil and two tributaries, Huai Sai tributary and Huai Nam Bo tributary. Water overtopping during the tropical depression, Sonca caused the Huai Sai Kamin embankment to breach. The breach occurred at two sites. One site was at the remnant of Huai Nam Bo tributary and the other site was at the irrigation conduit. An inadequate spillway capacity and inadequate maintenance were the causes of such water overtopping. The embankment of the Nong Sano reservoir was compacted of sandy lead clay (CL) over the sandstone, siltstone and mudstone of the Khorat Group. The Nong Sano embankment was breached due to the embankment that contained a significant amount of dispersive clay. Rehabilitation of the Nong Sano reservoir should consider the problem of the soil type used for constructing an embankment, while the rehabilitation of the Huai Sai Kamin dam should consider a spillway capacity and a proper maintenance.

Keywords: Dam failure, Dam incident, Earth-filled dam, Embankment, Geotechnical investigation

1. Introduction

A man-made dam is a construction to storage, control and/or diversion of water or any liquid-borne materials. Dams built with earth or rocks are called embankment dams. About 78% of world registered dams are the embankment constructions [1]. Typically, an embankment dam is constructed by a proper compaction of earth materials (gravel, sand, silt and clay) or a combination of earth and rock materials obtained from required excavation and borrow pits located near the dam site. Standard procedural constructions of an embankment dam include site investigation and materials for construction, engineering analyses, and a proper engineering design, construction, operation and maintenance. Proper engineering design, construction, operation and maintenance means the dam would accomplish its purposes and a failure of the dam should not occur before its life expectancy. Based on archaeological evidence, the age of the oldest man-made dam that is still in current use is about 3,300 years [2]. In Thailand, the first man-made dam was constructed in 1952, across the Chao Phraya River, the biggest river in the country [3]. Thereafter, many big and small dams were built across rivers throughout the nation. Most of these dams are the earth-filled type. At present, there are a total of 483 dams in Thailand. Of these 483 dams, 35 dams have the maximum water storage of greater than 100 million cubic meters, while the remainders have the maximum water storage between 1 and 100 million cubic meters [4].

Following a strike of tropical depression series [5-8] heavy rains and flooding have had sometimes occurred together with landslides and/or the breach of dams, reservoirs or road embankments throughout Thailand. In 2017, the notable dam breach incident occurred on July 28th at the Huai Sai Kamin dam, Sakon Nakhon province

(Figure 1). The breach of the Huai Sai Kamin dam was due mostly to water overtopping during a strike of a tropical depression, Sonca. Another notable dam breach incident occurred on October 18th at the Nong Sano reservoir, Lopburi province (Figure 2). The breach of the embankment of the Nong Sano reservoir was due to piping erosion at which time the reservoir water level was raised nearly to the maximum capacity of the reservoir. During storms or depressions, there were breaches of road embankments in several places. However, such road damages were often restored within a relatively short time period. Consequently, the failure of road embankments drew less public attention than the failure of dams or failure of water reservoir embankments. The failure of these two embankments attracted public attention and a call for dam safety assurance.

Figure 1 (A) Photograph of the Huai Sai Kamin dam taken in June 2015 from the Google Map showing the embankment crest, fillings in the reservoir and the water gate where the left conduit installed beneath the embankment [9], (B) and (C) photographs of the dam taken in the morning and in the afternoon of July 28th, 2017 after a breach incident occurred, the water gate shown in (A) was collapsed [10-11], (D) an aerial view taken on July 31st, 2017 showing the dam no longer held water and the remnant of Huai Nam Bo tributary that ran through the embankment [12].

The Huai Sai Kamin dam was built in 1953 to 1956 for irrigation purposes with its catchment area of 50 km^2 (Figure 3 (A)). It is a homogenous earth-filled embankment. Structure data of the dam are shown in Table 1. The Huai Sai Kamin embankment rests on Quaternary soils eroded from sandstone, siltstone and mudstone of the Khorat Group (Figure 3 (B)). The embankment was breached at two locations (Figure 4). One location was close the left end of the dam with a size of 20 meters wide, and 4 meters deep. The other location was at an irrigation conduit, about 25 meters away from the first one with the size of 50 meters wide, and 8-9 meters deep. The dam spillway was partially broken. A temporary rehabilitation of the dam was conducted by plugging the breached areas with nearby soils.

Figure 2 (A) Photograph of the embankment of the Nong Sano reservoir taken in July 2014 from Google Map, a square box outlined an approximate breached location that occurred in October 18th, 2017, an inserted photo showing a conduit installed for water outflow as water in a reservoir exceeds the maximum capacity [13], (B) and (C) photographs captured from video clip taken during the failure incident, showing an internal erosion through dispersive soil [14], (D) an aerial view showing a breached location and water in the reservoir [14].

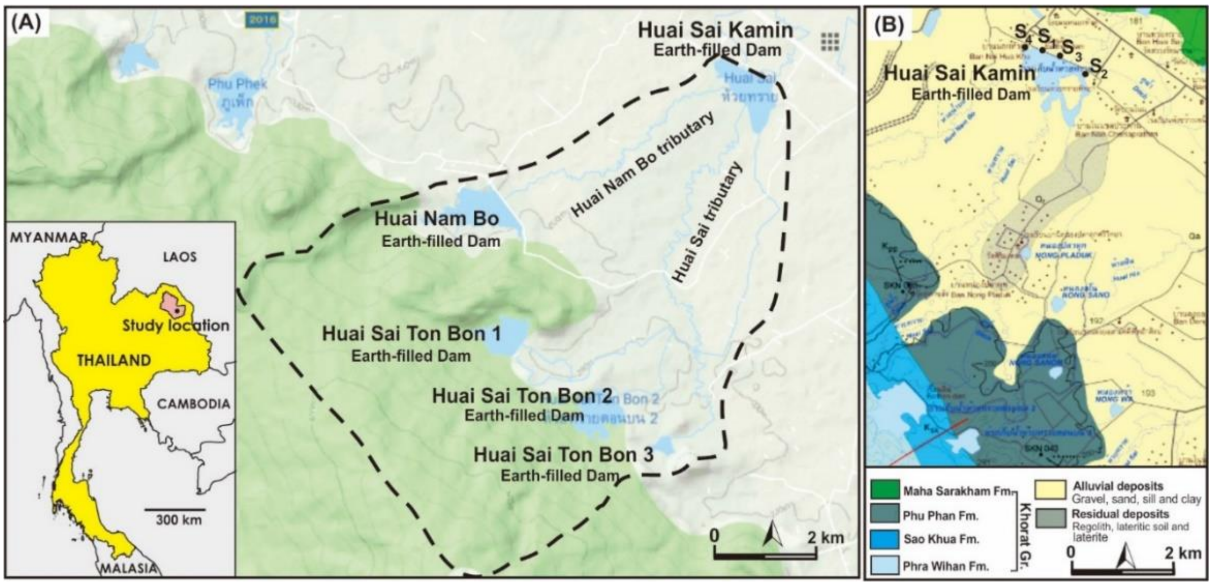

Figure 3 (A) Google map showing the topography of the Huai Sai Kamin dam and another four dams located upstream and within its catchment area; the catchment area is outlined by dash line [15]. An insert at the bottom left corner is an index map showing Thailand and study location. (B) Geologic map showing surface geology of the Huai Sai Kamin dam and surrounding areas, where soil samples were collected at 4 sites (S_1-S_4) [16].

Table 1 Characteristics of the Huai Sai Kamin earth-filled embankment [17].

Years built	1953-1956	Dam Crest	155.0 m*
Water storage area	1.44 km^2	Storage design level	154.0 m*
Storage capacity	2.4 million m^3	Spillway crest	154.2 m*
Embankment hight	8.3 m	Conduit level	151.2 m*
Embankment length	1,300 m	Conduit diameter	0.6 m left and right
Crest width	5 m	Type of spillway	Box spillway; 85 m^3/s
Base width	56.5 m	Irregation area	11.2 km^2
Upslope	1:3	Average rainfall	1,466.1 mm/year
Downslope	1:2.5	Catchment area	50.0 km^2

*An elevation appears to be mismatched with the topographic map (Figure 3 (A)), thus it was considered as a relative elevation.

The Nong Sano reservoir is considered to be a small reservoir with its maximum water storage of less than 1 million cubic meters (Figure 5). Because of its small type, the engineering design and construction records of the Nong Sano reservoir are not required to publish in the country database of dam and water reservoirs. The Nong Sano reservoir was built around 2004 to supply water. It has a catchment area of 0.64 km^2 and maximum water capacity of 0.7 million cubic meters [14]. A 0.6-meter diameter conduit was installed to drain water in case that reservoir water exceeds its maximum capacity (Figure 2 (A)). The reservoir embankment rests either on siltstone, sandstone and mudstone of the Khorat Group and/or Pleistocene river terrace deposits of gravel, sand, silt, clay and lateritic soil (Figure 5).

Figure 4 An aerial view showing the two breached sites of the Huai Sai Kamin embankment, one site at the left water gate and about 25 meters away from the other site. An insert photo shows embankment cross section in the opposite view [11,18].

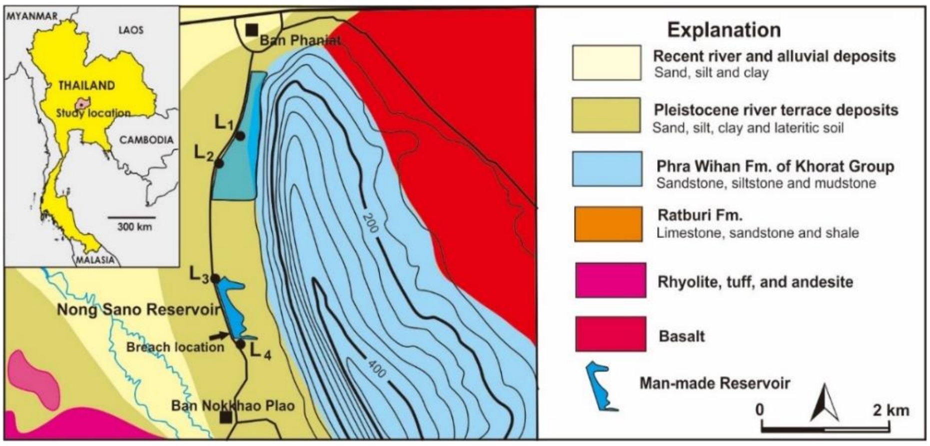

Figure 5 Geologic map showing surface geology of the Nong Sano reservoir and surrounding areas. Soil samples were obtained at 4 sites (L1-L4) [19]. An insert at the top left corner is an index map showing Thailand and study location.

Any man-made earth structures, including earth-filled embankments that rest on or contain dispersive clays require a special treatment and/or a proper engineering design and construction due to the highly erodible propensities of the clays [20-21]. The requirement for special treatment and/or a proper engineering design and construction of a structure built with dispersive clays have been recognized since 1960s. Research study showed that piping failure of many small earth-filled dams in Australia was due to using dispersive clay [20,22]. Of further note, the first remarkable piping failure incident in Thailand occurred in 1990 at an earth-filled dam, Mun Bon dam [23]. Fortunately, such piping failure incident was quickly observed and restored. Indeed, a comprehensive investigation into the potential failure causes as well as risk and other assessments were conducted before the Mun Bon dam was fully rehabilitated. The failure of the Mun Bon dam indicates the presence of dispersive clay in some places in Thailand, and any man-made earth structures should therefore be aware of dispersive clay propensities. A precaution of rapid erosion of dispersive clay should be considered prior to construction of the earth structures especially of large (the maximum water storage of greater than 100 million cubic meters) or medium (the maximum water storage between 1 and 100 million cubic meters) type of dam [19]. To-date, the Mun Bon dam has still been in operational. For the Nong Sano reservoir, it appears to be a lack of precaution and awareness of dispersive clay during the construction. Further, no remedial work was performed although severe gully erosion and cracks of the embankment were obviously visible at slope faces and the crest (i.e., Figure 2 (A)). The Nong Sano reservoir embankment lasted for about 13 years before its embankment failed in the morning of October 18th, 2017. The water flew out from the reservoir as a small hole, but later the hole became widened till the soils above the hole collapsed i.e., a breach occurred (Figures 2 (B)-2 (D)). The reservoir no longer held water. At the time of the failure incident, the reservoir water volume was about 0.6 million cubic meters. This water volume did not exceed the maximum reservoir capacity of 0.7 million cubic meters. Rehabilitation was conducted immediately after the reservoir water level fell to the bottom of the reservoir by using wood piles and big bags filled with nearby soils.

This paper presents results of an investigation into geotechnical causes of failure of earth-filled embankment that occurred in Thailand in 2017. The aim of the study was to provide a better understanding of failure causes that should pave the way to a proper design, treatment and restoration of embankments regardless of large or small type. Moreover, this paper demonstrated the utility 2-D resisitivity imaging in determining heterogeneous internal structures of the earth-filled embankment.

2. Materials and methods

Hydro-meteorological data, topography, and geological and geophysical data of the study sites were sought. In addition, photographs and videos from television news and newspapers were assembled. Site visits were performed to inspect and to collect soil samples together with an interview of some local people concerning dam failure incidents. Two samples of disturbed soils were taken from embankment materials (S_1 and L_1). Soil sampling locations are indicated in Figures 3 (B) and 5. Additional six samples of disturbed soils samples from the locations shown in Figures 3 (B) and 5 were obtained 30 cm below ground surface. Soil samples were tested for basic properties based on ASTM standard, including field water content, grain size distribution, Atterberg's limit, specific gravity, standard compaction, and crumb test. Classification of soil samples were based on the

Unified Soil Classification System, USCS. Field and laboratory test data were subjected to analysis and interpretation.

3. Results and discussion

Surface geology of the Huai Sai Kamin dam and the Nong Sano reservoir are shown in Figures 3 (B) and 5 together with their surrounding areas. The Huai Sai Kamin dam is situated on alluvial deposits that are composed of gravel, sand, silt and clay particles. Sources of these particles were mainly weathered and eroded from sedimentary rocks of the Khorat Group as indicated in Figure 3 (B). The Nong Sano reservoir is situated on Quaternary terrace deposits that are composed of sand, silt, clay and laterite. Sources of the terrace deposits were probably weathered and eroded from sedimentary rocks of the Khorat Group and from extrusive igneous rocks as evident in Figure 5. Tables 2 and 3 present test results of samples of materials from embankments and nearby the embankments, respectively. According to the USCS, the soil used for constructing the Huai Sai Kamin embankment is clayey sand (SC) and is not dispersive soil. The soil used as a construction material for Nong Sano embankment is sandy lead clay (CL) and consists of dispersive (Grad 3). The soils nearby the Huai Sai Kamin embankment are well graded-sand with gravel (SW) or poorly graded sand with gravel (SP) and non-plasticity (NP), while the soils nearby the Nong Sano embankment are poorly graded sand with gravel (SP) and non-plasticity (Table 3). The soils nearby these two embankments are mostly sand particles with few silt and clay particles. Data in Tables 2 and 3 indicate that silt and clay particles used for constructing these two embankments were not close to ground surface (30 cm. ground surface) at the dam site. Hence, silt and clay particles were below 30 cm or they were borrowed from other places. Moreover the clay particle used for constructing the Nong Sano embankment is dispersive clay. According to geologic map shown in Figure 5, sources of the dispersive clay at the Nong Sano reservoir appear to be resulted from weathering and erosion of extrusive igneous rocks, basalt, rhyolite, tuff and andesite.

Figure 6 (A) provides daily rainfall for July 2017 recorded by the rain gage station nearby the Huai Sai Kamin dam. Figure 6 (B) provides daily rainfall for October 2017 recorded by the rain gage station nearby the Nong Sano reservoir. The Huai Sai Kamin embankment was breached on July 28th, and according to data shown in Figure 6 (A) the amount of rainfall was 203 mm, i.e., heavy rainfall. Water capacity in the reservoir was exceeded a maximum capacity of 127% [4]. The Nong Sano embankment was breached on October 18th, 2017, and according to data in Figure 6 (B), the amount of rain was 2.5 mm. Figure 6 (B) indicates the Huai Sai Kamin embankment breached as a result of heavy rainfall.

Table 2 Properties of embankment materials.

Test/property		Huai Sai Kamin embankment, S_1	Nong Sano embankment, L_1
Moisture contents (%)		7.96	5.56
Sieve Analysis and Hydrometer	Gravel (%)	13.25	0.05
	Sand (%)	51.87	28.12
	Silt (%)	27.74	45.78
	Clay (%)	7.14	26.05
Atterberg's Limits	Liquid limit	27.50	35.77
	Plastic limit	20.35	17.71
	Plastic Index	7.25	17.40
USCS classification		Clayey sand (SC)	Sandy lead clay (CL)
Specific gravity (kg/m^3)		2,540	2,140
Dry density (kN/m^3)		19.80	16.40
Crumb		N/A	Dispersive (Grade 3)

Table 3 Properties of soils nearby embankments.

Test/property		Huai Sai Kamin			Nong Sano		
		S_2	S_3	S_4	L_2	L_3	L_4
Moisture contents (%)		14.30	13.31	16.66	1.59	1.81	1.35
Sieve Analysis and Hydrometer	Gravel (%)	21.57	16.70	4.70	0.95	4.14	7.37
	Sand (%)	77.80	81.55	90.98	98.00	94.64	92.15
	Silt and Clay (%)	0.63	1.75	4.32	1.05	1.22	0.48

Test/property		Huai Sai Kamin			Nong Sano		
		S_2	S_3	S_4	L_2	L_3	L_4
Moisture contents (%)		14.30	13.31	16.66	1.59	1.81	1.35
Atterberg's Limits	Liquid limit Plastic limit Plastic Index	NP	NP	NP	NP	NP	NP
USCS classification		SW	SP	SP	SP	SP	SP
Specific gravity (kg/m^3)		2,522	2,637	2,633	2,686	2,644	2,675
Dry density (kN/m^3)		19.10	15.26	17.62	17.38	18.54	19.00

NP = Non plasticity; SW = Well-graded sand with gravel; SP = Poorly graded sand with gravel

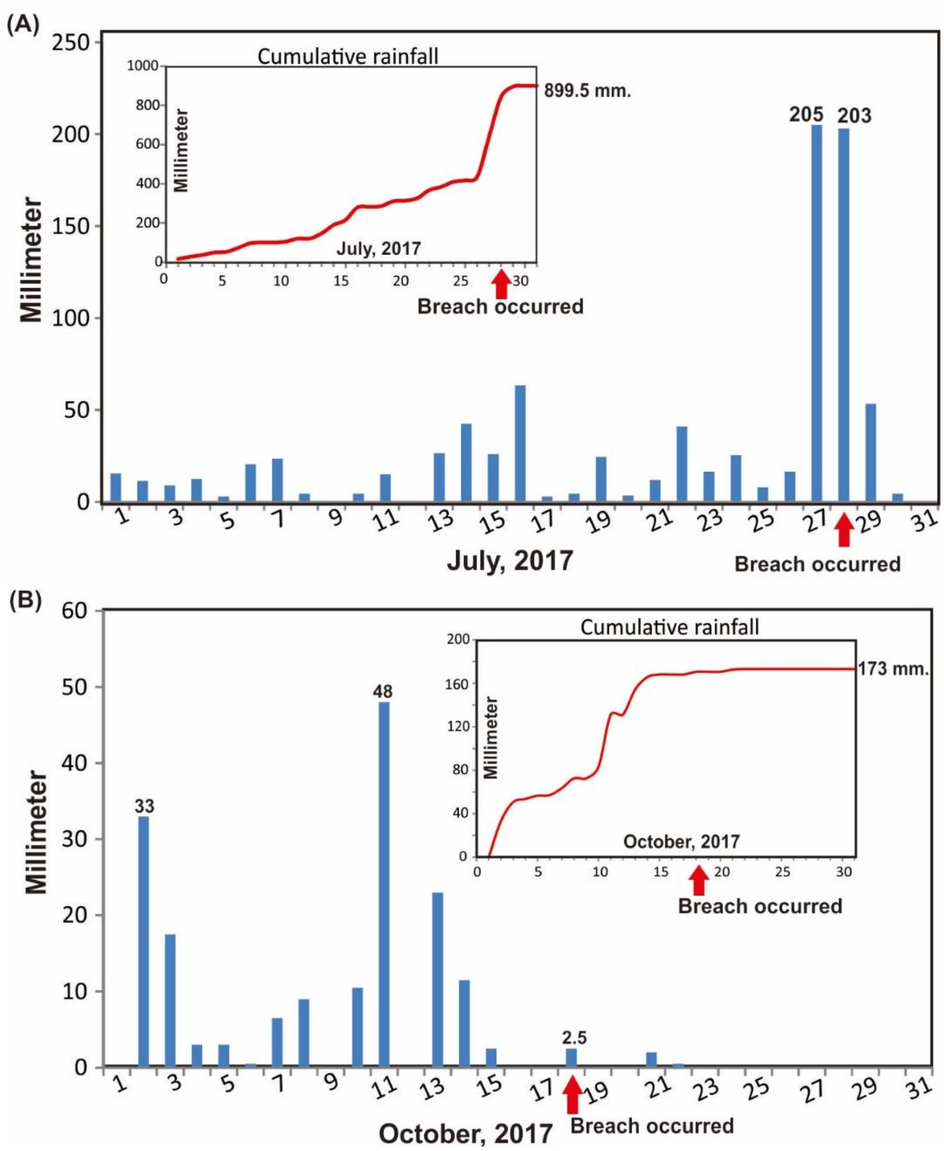

Figure 6 Daily rainfall and cumulative rainfall for July 2017 recorded by (A) the rain gage station nearby the Huai Sai Kamin dam [24], (B) daily rainfall and cumulative rainfall for October 2017, recorded by the rain gage station nearby the Nong Sano reservoir [24].

Figure 7 displays the rainfall over 48 hours from 7.00 a.m. of July 27th to 7.00 a.m. of July 29th, 2017 recorded by the rain gage station nearby the Huai Sai Kamin dam. As reported by local people, the Huai Sai Kamin embankment was breached around 8.00-9.00 a.m. of July 28th but the rain continued till 6.00 p.m. A cumulative rainfall between 7 a.m. of July 27th to 10.00 a.m. of July 28th was 344 mm. The dam was breached as a result of water overtopping of the dam. The water overtopping later triggered the dam to breach. Although the dam has a spillway with a rate of 85 m^3 per second (Table 1), this capacity appeared to be inadequate with the resultant water overtopping. Moreover, Figure 8 shows dense and large debris of water weed and water plants that blocked water flow to the spillway. These dense and large debris volumes reduced the spillway capacity. The dense and large water weed and water plants indicated an inadequate maintenance of the dam. Figure 4 displays the breach occurred at two locations, near the left end of the embankment and at the left irrigation conduit. In fact, the breach occurred at the conduit was not unusual as it was already anticipated as a high failure prone.

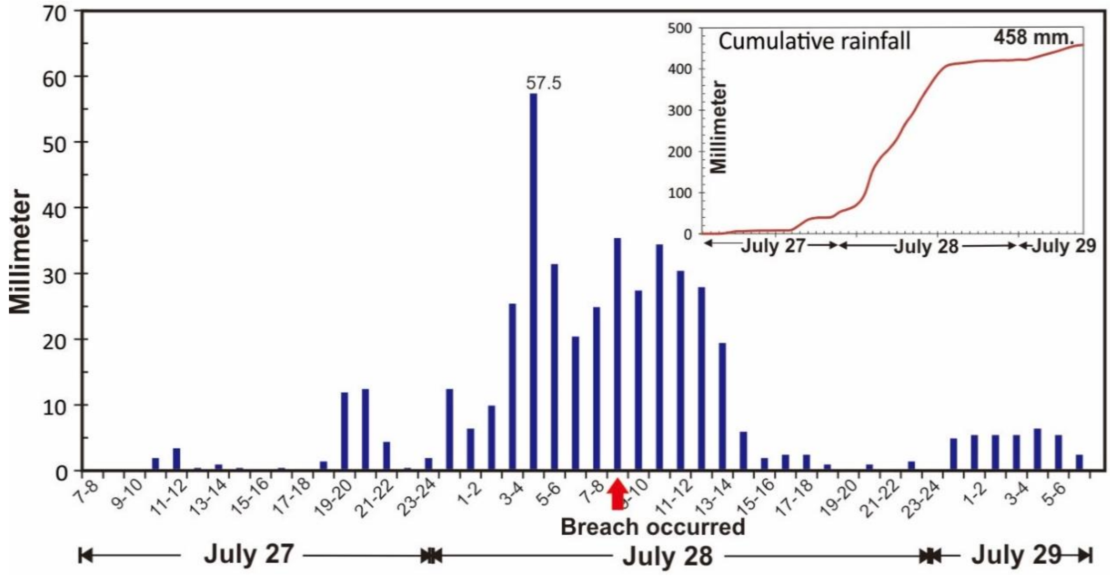

Figure 7 A 48-hour rainfall from 7.00 a.m. July 28th to 7.00 a.m. July 29th, 2017, recorded by the rain gage station, nearby the Huai Sai Kamin dam [24].

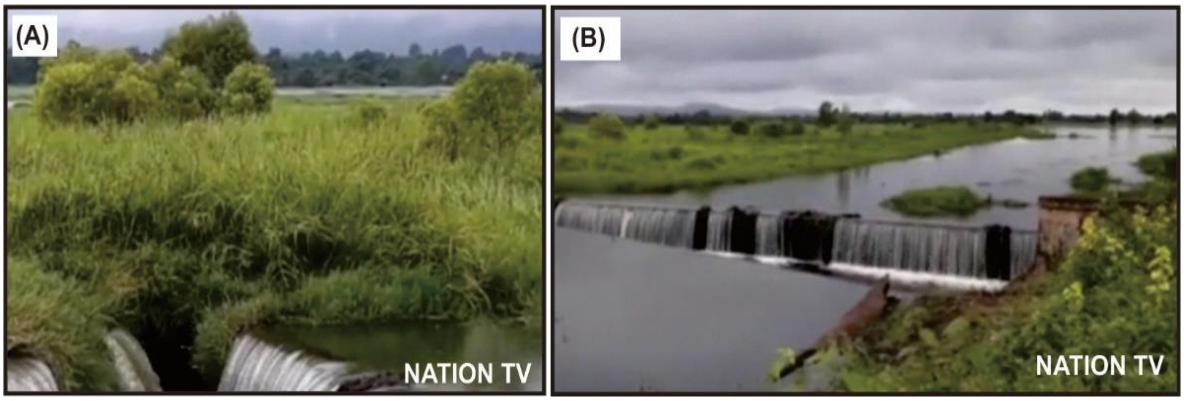

Figure 8 (A) Photograph showing the spillway blockage with water weed [25], (B) a wide view showing thick and dense water weed floating close to the spillway [25].

Figure 9 (A) shows resistivity locations that were acquired at the Huai Sai Kamin dam. Figure 9 (B) displays resistivity section acquired along the top of embankment. Figure 9 (C) shows resistivity section acquired along the downstream toe of embankment. Subsurface anomaly of low resistivity zone was evident between the distances of 440-470 m and 12-25 m deep in Figure 9 (B). This low resistivity zone corresponded with a body of river channel of the Huai Nam Bo tributary as surface evidence shown on aerial photographs in Figures 1 (D). This zone was the deepest breaching zone occurred (Figures 1 (A), 4 and 9 (C)). Figures 1 (A), 4 and 9 indicate that the Huai Sai Kamin embankment was built on top of the Huai Nam Bo tributary. The remnant channel of the

Huai Nam Bo tributary was the weakest zone accounting for the failure at the base of the Huai Sai Kamin dam. Figure 9 (C) shows a low resistivity zone existed between the distances of 230-580 m and 0-32 m deep. Based on soil testing results presented in Table 3, the low resistivity zone in Figure 9 (C) was a high moisture content zone, not a zone with high clay content. The local soil nearby the embankment is SP or SW.

As indicated in Figure 6 (B), a cumulative monthly rainfall of the Nong Sano reservoir was 173 mm. The amount and pattern of rainfall differed from the case of the Huai Sai Kamin dam. No evidence of heavy rainfall hit the Nong Sano reservoir during its failure. Further, the failure occurred at the time when amount of water in the reservoir was below the reservoir maximum capacity. Figure 2 (A) displays gully erosion at the embankment of the Nong Sano reservoir. The gully erosion was obviously evident and the gully erosion appearing in Figure 2 (A) is the evidence of dispersive clays. Hence the failure of the Nong Sano reservoir is a result of piping erosion resulting from using dispersive clay as an earth-filled material. Figure 10 displays three additional reservoirs close to the Nong Sano reservoir, where the gully erosion and milky water were more obviously evident than the Nong Sano reservoir. Hence, it is envisaged that a similar failure will repeat if no proper treatment and/or proper reconstruction is undertaken for the Nong Sano reservoir and the other three reservoirs nearby.

The failure of the Nong Sano reservoir calls for a precaution and awareness of the reservoir safety when storm hits as well as when the reservoir holds large amount of water. In addition the failure of the Nong Sano reservoir suggests that regular check, inspection and monitoring of cracks and erosion features of the embankment should be undertaken in a proper manner. Hence, proper remedial actions should be taken when cracks and erosion features continue expansion. The Nong Sano reservoir lasted about 13 years. This implies an unpredictable life-span when dispersive clays are utilized as one of construction materials.

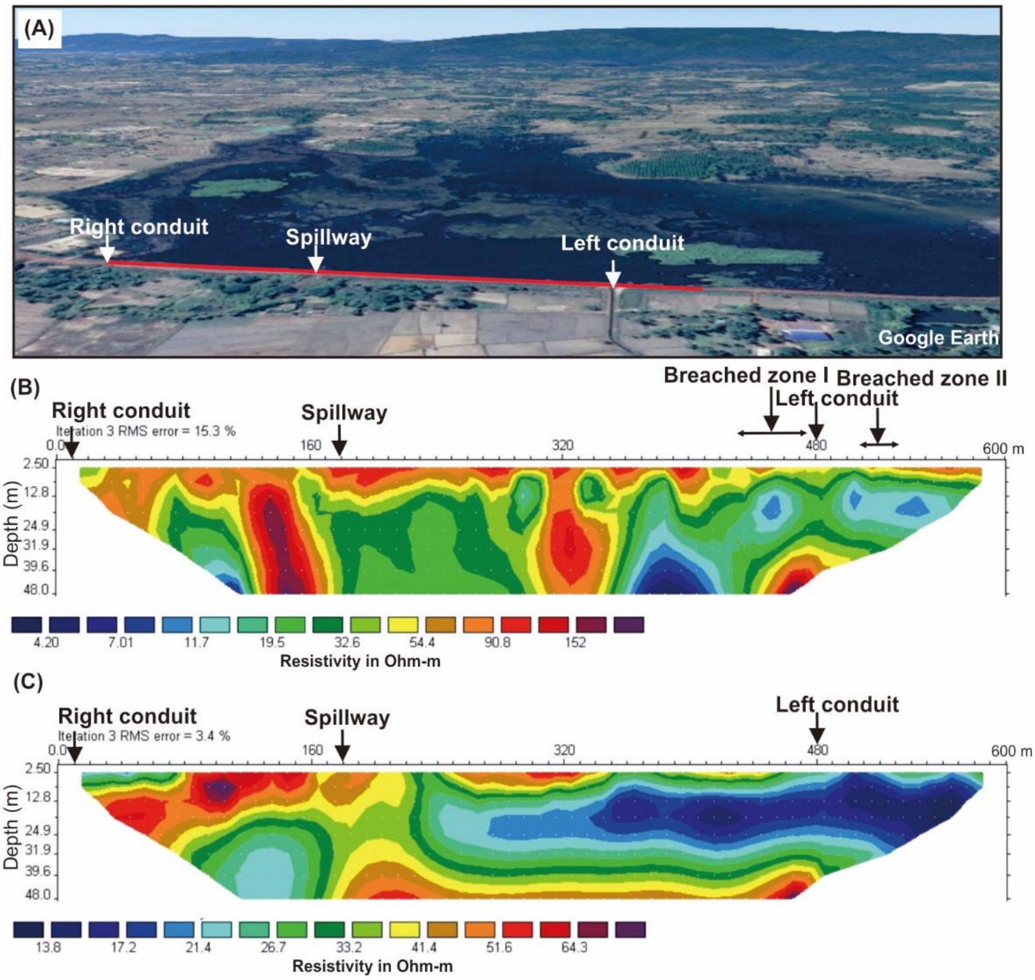

Figure 9 (A) An oblique view of the Huai Sai Kamin embankment from Google Earth showing 2-D resistivity line location that was acquired in 2009 [26-27], (B) pseudosection of the 2-D resistivity along the top of the embankment, where high moisture zone is indicated at the left embankment [27-28], (C) pseudosection of the 2-D resistivity along the downstream toe of the embankment, where a high moisture content is indicated at the left [27-28].

4. Conclusions

In 2017, there were two prominent earth-filled embankment failure incidents in Thailand; the Huai Sai Kamin dam and the Nong Sano reservoir. The failure of the Huai Sai Kamin dam occurred after 61 years of operation, while the failure of the Nong Sano embankment occurred after 13 years of operation. Results of the present study have shown that water overtopping caused the Huai Sai Kamin embankment to breach. In addition, the 2-D resistivity image and aerial photograph have indicated the deepest breached zone to be the remnant of the Huai Nam Bo tributary on top of which the Huai Sai Kamin embankment dam was built. The water overtopping of the Huai Sai Kamin dam was caused mostly by an inadequate spillway capacity and inadequate maintenance. The Nong Sano embankment was breached due to the embankment that contained a significant amount of dispersive clay.

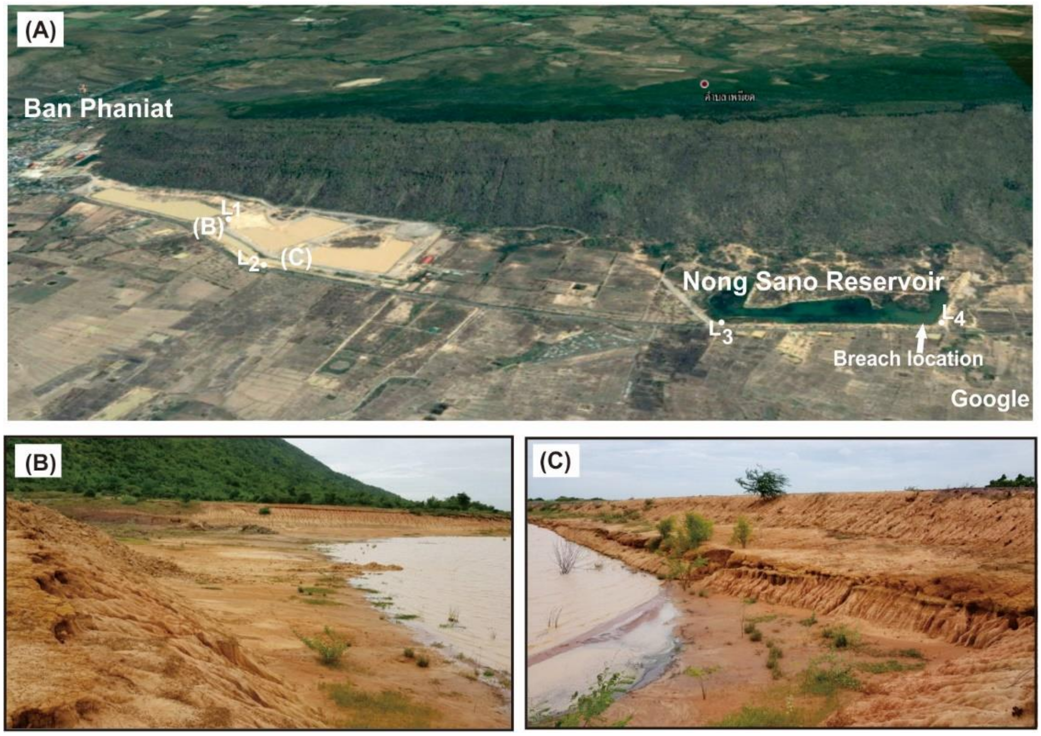

Figure 10 (A) A satellite oblique view of the Nong Sano reservoir and another three reservoirs nearby [29], L_1-L_4 are locations of soil samples, (B) and (C) photographs taken from the location marked in (B) and (C), showing gully erosion feature and milky water in the reservoirs.

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