Jordan Journal of Civil Engineering, Volume **14**, No. **1**, **2020**

Estimation of Failure Surface of Pa Bon Dam from Site Investigation

Kobid Panthi [1] ***and Suttisak Soralump*** [2]

[1] Graduate Student, Department of Civil Engineering, Kasetsart University, Bangkok, Thailand.
E-Mail: kobid.p@ku.th
[2] Associate Professor, Department of Civil Engineering, Kasetsart University, Bangkok, Thailand.
E-Mail: soralump_s@yahoo.com

ABSTRACT

Soil Investigation work is carried out in geotechnical engineering for the determination of soil properties. Various soil investigation works were carried out in the upstream slope of Pa Bon dam after the movement of upstream slope on July 27, 2014. Bore hole investigation, resistivity test, echo sounding and SASW (Spectral Analysis of Surface Waves) were conducted in the failure zone to determine the failure surface and provide the rehabilitation work accordingly. Likewise, results from piezometer were also used to determine the flow of water in the failure zone. The investigation work has helped in determining the probable failure surface and rehabilitation work has been proposed accordingly.

KEYWORDS: Embankments, Site investigation, Slope failure, Slope stabilization.

INTRODUCTION

Pa Bon dam is a 45 m high dam with a length of 750 m located at Patthalung Province, Thailand. The construction of the project began in 1994 and it started its commercial operation in 2004. The dam consists of: impervious clay core, shell zone, boulder riprap, soil foundation, granite rock foundation and filter material. The chimney drain and blanket drain with a thickness of 2 m are provided for draining out the water from the clay core and preventing the downstream slope from being saturated. The cross-section of Khlong Pa Bon dam is shown in Figure 1. The first movement of the upstream slope was observed in 2014. The geological profile along the center line of the dam is shown in Figure 2.

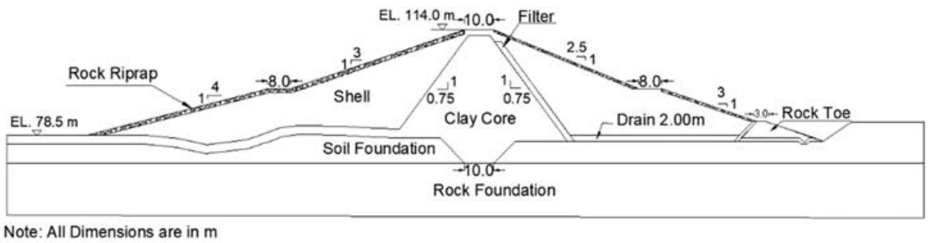


Figure (1): Cross-section of Khlong Pa Bon dam (0+272m)

Received on 1/2/2020.
Accepted for Publication on 9/2/2020.

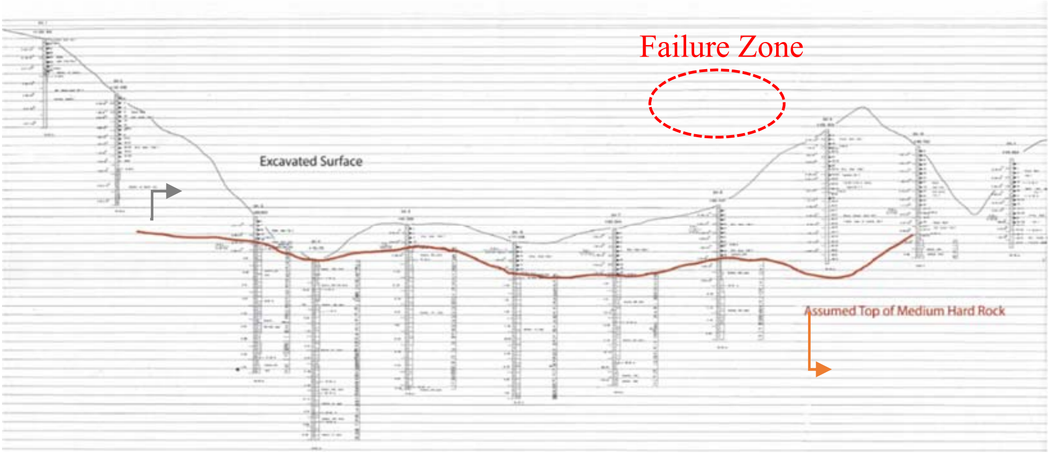


Figure (2): Geological profile along the center line of the dam (Source: Royal Irrigation Department, Thailand)

The movement was specifically observed at three locations; i.e., 0+272, 0+297, 0+332 meters and their vicinity. From the initial inspection, it was found out that the horizontal movement was approximately 80 meters, while the vertical movement was 2 meters (Figure 3). After failure, maintenance work was carried out by excavating the estimated failure zone and re-compacting it with stock material (Figure 4).

Figure (3): Upstream slope of Pa Bon dam after the first movement

Figure (4): Rehabilitation work after first failure

The proposed excavation plan is shown in Figure 5, but excavation could not be completed as per design. Excavation 1 and excavation 2 (Figure 5a and Figure 5b) were executed as per design, but soon after the second excavation, cracks were observed at the slope and the top of the crest, as shown in Figure 6.

So, excavation work was halted and the slope was rehabilitated without excavating the third portion (Figure 5c). Consequently, general operation of the dam continued after its maintenance. Since the movement of the dam did not stop even after the rehabilitation work, various site investigation works were carried out to determine the probable failure surface.

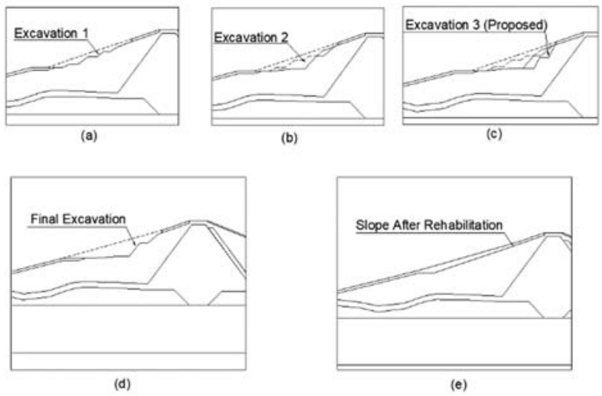


Figure (5): (a) Excavation 1, (b) excavation 2 (c) proposed excavation 3, (d) dam after excavation and (e) dam after filling and compaction

Figure (6): Observation of cracks at the crest of the embankment during excavation

SITE INVESTIGATION

Soil Investigation work in geotechnical engineering has been carried out by various researchers using various site investigation techniques (Budhu, 2013; Clement and Moreau, 2016; Soralump, Panthi et al., 2018; Shrestha, Jotisankasa et al., 2019). For the investigation of failure surface in Pa Bon dam, bore hole test, resistivity test, echo sounding and SASW were conducted. The results from these tests have been used for the estimation of probable failure surface.

Bore Hole Investigation

Bore hole investigation in Pa Bon dam was carried out after the observation of the first movement in 2014 (Figure 9). The investigation was conducted in 3 sections (i.e., 0+272m, 0+297m and 0+332m) with three bore holes in each section. These locations were chosen based on visual inspection of the upstream slope movement. The depth of excavation was in the range of 8 – 10 m, as shown in Figure 7. From the investigation, it can be seen that the top of the shell zone consists of a silty sand layer, followed by the presence of silty clay with some fragments of gravel and rock.

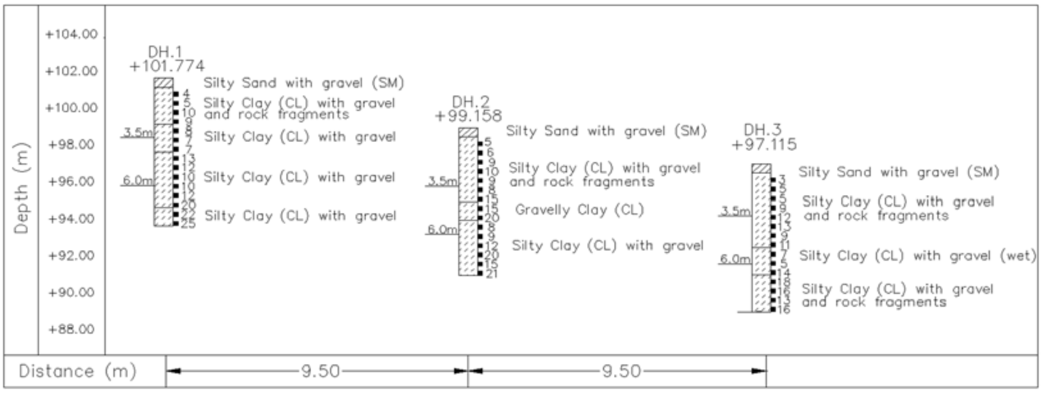


Figure (7): Bore hole investigation at failure zone; i.e., 0+272m (2014)

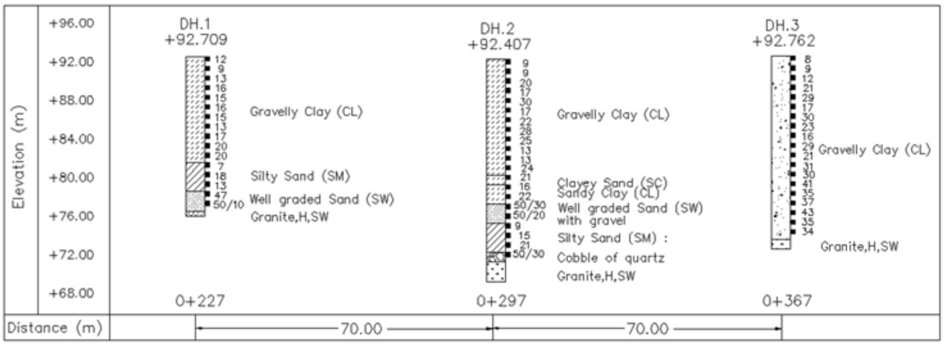


Figure (8): Bore hole investigation at toe zone (2017)

Failure surface was found to be in a section containing silty clay with gravel for all the investigated sections. The corrected N value (N60) in each section (0+272, 0+297 and 0+332) was determined from this test. From the investigation, the reduction in N value was observed at two sections; i.e., around 3.5 meters and 6 meters (Figure 7) and was preliminarily identified as the location of failure surface.

Figure (9): Conduction of bore hole investigation after the movement of the slope in 2014

The surface of failure was assumed to be 3.5 meters below the ground surface and rehabilitation work was carried out, but the movement of the dam did not stop, but rather increased each year. The test was again conducted at 0+227, 0+297 and 0+367 in 2017 near the toe zone to evaluate the existing condition. From the investigation, the toe of the dam looked intact, but at +82.00 meters, it seemed to have undergone some reduction in strength and has the possibility of failure in a long run (Figure 8).

Hence, from the investigations in 2014 and 2017, the surface of failure was estimated, as shown in Figure 10. A total of three curvilinear failure surfaces were estimated from the bore hole investigation. Two shallow failure surfaces and one probable deep failure surface were estimated based on the logging results.

Geophysical Survey (Electrical Resistivity Test)

Electrical resistivity test is a widely used geophysical test for the determination of soil properties in geotechnical engineering. Various research works have been carried out for determining the effectiveness of this testing method (Calamita, Brocca et al., 2012; Veselý, Konečný et al., 2015; Clement and Moreau, 2016; Park, Lee et al., 2017; Ranjy Roodposhti, Hafizi et al., 2019). Geophysical survey in Pa Bon dam was conducted to detect the areas having different electrical resistances and to specify the position showing both low and high abnormalities. The test was conducted in three elevations (i.e., 114.0m, 109.27m and 98.36m) and in three sections (0+272m, 0+297m and 0+332m), as shown in Figure 11.

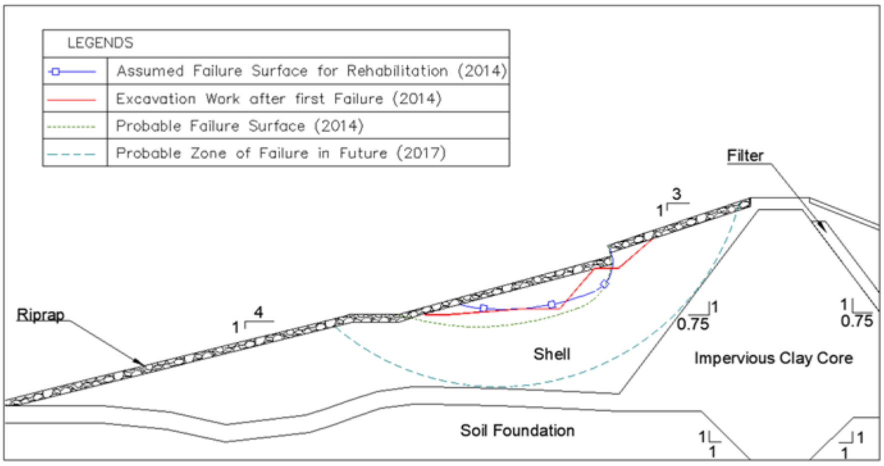


Figure (10): Failure surface estimated from bore hole investigation (2014 and 2017)

Field data was analyzed using Res2dinv version 3.59 showing the specific electrical resistance values. Apparent resistivity was categorized into 5 ranges according to the resistivity values, as shown in Table 1. The results obtained from electrical resistivity test were compared with results from bore hole geological inspection, as shown in Figure 12. The anomalous area was identified as the area with resistivity in the range of 0-100 ohms and failure surface was drawn accordingly. The results obtained were compared with N-values obtained from bore hole investigation. It was found that the zone having N–values less than 12 could be categorized as very soft to stiff clay.

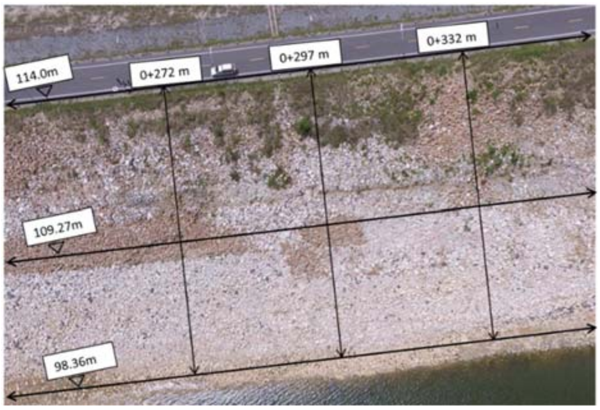


Figure (11): Location for the conduction of electrical resistivity test

Table 1. Apparent resistivity for various phases

Phase	Resistivity (ohms)	Remarks
Phase 1	0-100	Consists of the insertion of water between soil grains indicating the disturbance or loss of properties from original
Phase 2	101-125	Lower humidity and higher resistivity than phase 1
Phase 3	126-225	Intermediate zone with resistivity greater than phase 2
Phase 4	226-275	Dry soil or the boundary between the soil filling the dam and the soil foundation; i.e., transition zone
Phase 5	>275	Zone consisting of very dry, tight, hard or rocky soil foundations

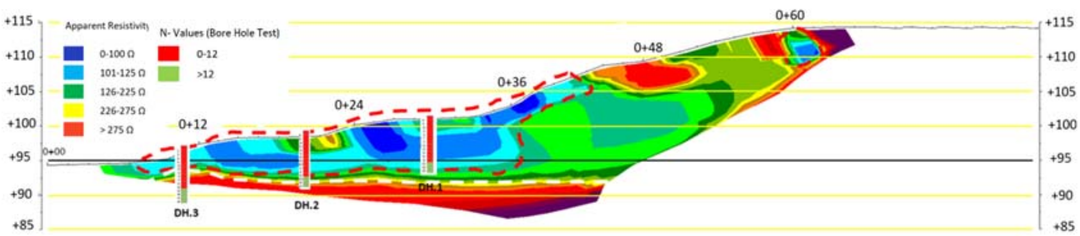


Figure (12): Comparison of results from resistivity test and bore hole investigation (0+272 m)

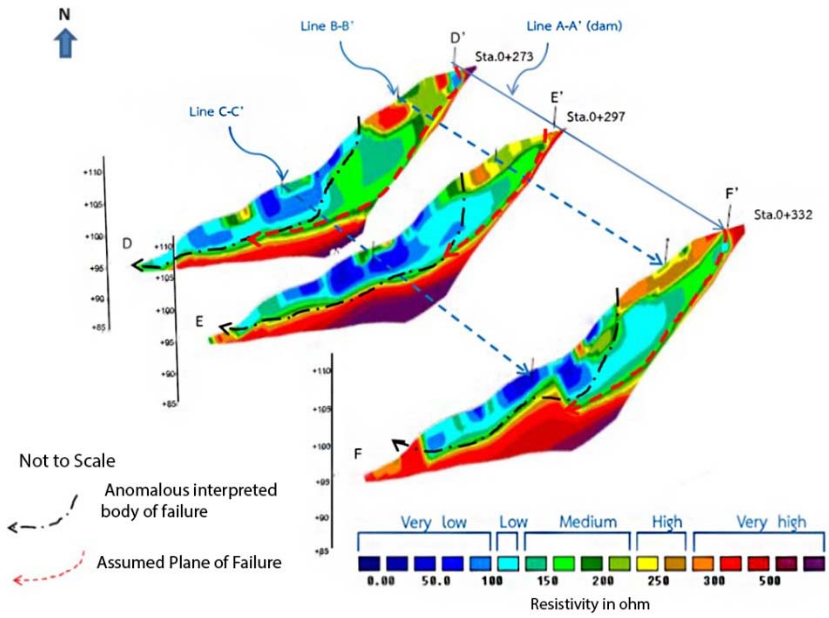


Figure (13): Diagram showing the pattern and extent of slope movement from electrical resistivity test

Likewise, the area with high electrical resistance and having N-value greater than 12 was categorized as stiff to hard clay (silty clay). It was found that the results from electrical resistivity test and bore hole investigation are consistent for all the locations tested. The failure surface was obtained for three sections, where the investigation was conducted, as shown in Figure 13. The results show the shallow immediate surface of failure for all sections as well as a probable deep failure surface. The section with very low resistivity needs immediate attention, but in the long run, the section with medium resistivity might also fail along with other zones. So, attention is required to prevent further movement of the slope in the future.

Echo Sounding

Echo sounding is the most widely used depth measurement technique for surveying river and harbor navigation projects, transmitting sound waves into the water (Shatnawi, 2012). Echo sounding was conducted in Pa Bon dam to observe the extent of slope movement in 2017. The exploration was carried out using the HYDROTAC II Echosounder.

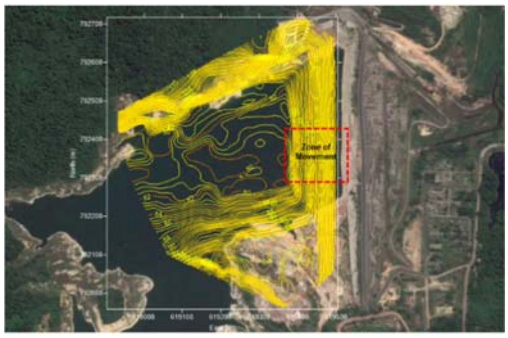


Figure (14): Plan section showing the results of echo sounding

The upstream of Pa Bon canal basin has an area of approximately 40,000 square meters. The exploration was conducted covering the area parallel to the basin in every 20 meters. The result obtained from echo sounding is presented in Figure 14. The result was compared with the slope of the embankment structure before its failure (Figure 15).

The plan view shows the zone of movement in the embankment structure. Likewise, the cross-section was plotted at every 20 meters and was compared with the initial condition of embankment structure. There was no major movement observed at other sections, but it was distinctly visible at the failure zone; i.e., 0+270 – 0+350 meters. The movement of the slope at 0+297m is as shown in Figure 15.

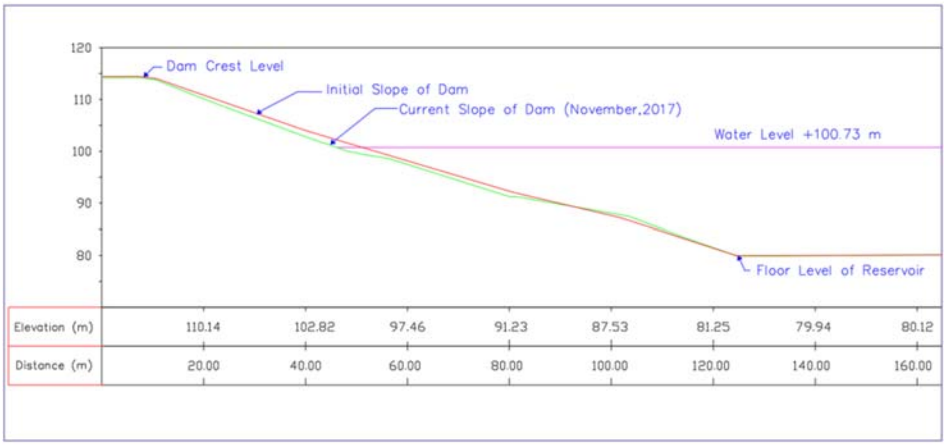


Figure (15): Cross-section of embankment at failure location (0+297)

SASW (Spectral Analysis of Surface Waves)

SASW test was conducted on Pa Bon dam in between 4-5 November, 2017 to determine the shear wave velocity of the dam core at various depths. This test was also used to evaluate the nature of foundation stone. The spacing between wave source and first receiver and between first receiver and second receiver ranged from 0.5 to 50 meters. A hammer of 300 kg weight was used to create high frequency and obtain data for higher depths. By analyzing the data obtained in the field, dispersion curves (graphs between wave velocity and Rayleigh waves) were plotted for the determination of shear wave velocity. A total of 5 SASW tests were conducted at various test locations, as shown in Table 2.

Small strain stiffness (G) has been used as an indicator for the structure health (Shrestha et al., 2019) and it can be determined from the shear wave velocity obtained from SASW test (Cha, Santamarina et al., 2014) as given by Equation 1.

$$G = \delta * v_s^2 \qquad (1)$$

Table 2. Details of SASW testing at Pa Bon dam

Test No.	Description	Chainage (m)
Vs 1	Test location at maximum section	0+120
Vs 2	Test location in the area of settlement above water 1	0+310
Vs 3	Test location in the area of settlement above water 2	0+375
Vs 4	Test location where there is no subsidence above the water	0+525
Vs 5	Test location on the shallow rock foundation	0+700

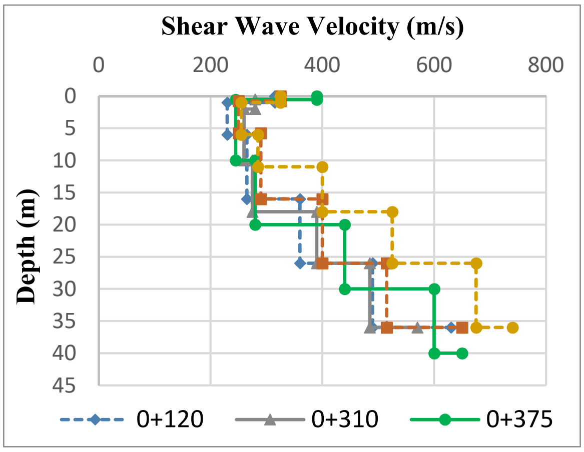


Figure (16): Comparison of shear wave with depth for failure and non-failure zones

The values of small-strain shear stiffness for the failure zone (0+310m) for various depths were calculated using Equation 1 and are given in Table 3.

The preliminary failure zone is estimated at around 6m from the crest of the dam and as can be seen, the G modulus in that section is 15,000 kPa, indicating an intact core. It can hence be confirmed that the core zone had not undergone any reduction in shear strength.

Table 3. Calculation of small-shear stiffness for the failure zone (0+310m)

Depth to Top of Layer (m)	Layer Thickness (m)	Shear Wave Velocity (m/sec)	Assumed Values			G Modulus (kPa)
			P-Wave Velocity (m/sec)	Poisson's Ratio	Mass Density, tons/m^3	
0	0.5	320	599	0.3	2	20,480
0.5	1.5	280	524	0.3	2	15,680
2	8	260	486	0.3	2	13,520
10	8	275	515	0.3	2	15,125
18	8	390	730	0.3	2	30,420
26	10	485	907	0.3	2.1	49,397
36	11	570	1066	0.3	2.1	68,229

Piezometer

The piezometer at Pa Bon dam was installed at 0+130 m, as shown in Figure 17. The analysis was based on the assumption that the movement of water in this location is similar to that in the failure zone. Most of the piezometers are located in the impervious clay core for detection of water in the core zone. 2 piezometers are located in the downstream slope to detect the presence of water, if any, while one piezometer is located at the blanket drain to determine its functionality.

Instrumentation results from various piezometers were compared with exact water levels observed during that period of time. The comparison of results obtained from various piezometers in the clay core from 2500 days to 5000 days is shown in Figure 18. The results from all the piezometers in the clay core indicate that the permeability of the clay core is very low and no significant variation of water level was observed in piezometer with actual fluctuation of water level. This behavior is observed for all the piezometers installed in the clay core as shown in Figure 18.

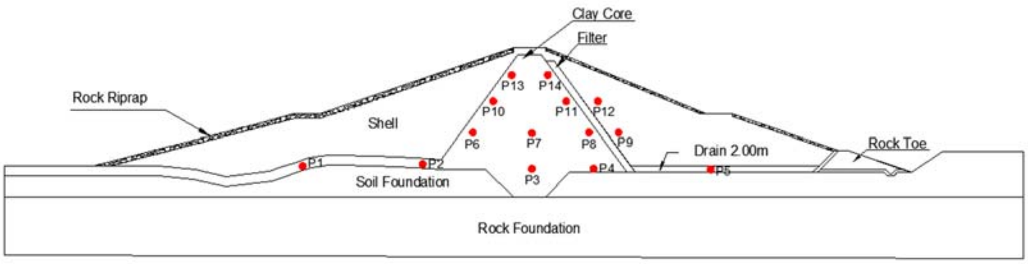


Figure (17): Piezometer installation at Pa Bon dam

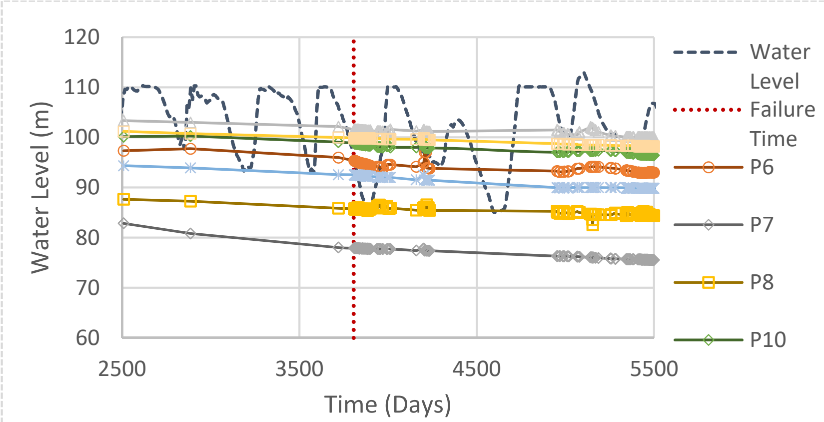


Figure (18): Variation of water level in piezometer with water level fluctuation

Estimation of Failure Surface

The failure surface of the embankment structure was determined from various site investigations (Figure 19). Bore hole investigation and electrical resistivity test helped in determining the failure surface. Likewise, SASW test helped in verifying that the core was intact and had not undergone any movement. It further helped in confirming the failure surface obtained from previous investigations. The results obtained from these tests helped in determining the actual failure surface. The current status of the slope of the embankment and the length of movement were determined from echo sounding test.

Rehabilitation Work

The movement of upstream slope of Pa Bon dam started in 2014 and has been continuing to date. After failure, the soil was assumed to have undergone reduction in shear strength and residual shear strength was calculated using reversal direct shear test (Panthi and Soralump, 2020). To prevent further movement of the slope, berm construction on the upstream slope was proposed from chainage 0+145 to 0+405m. Since the width of the failure zone has been increasing each year, the berm length has also been increased. Berms with a slope of 1:2 and each berm having 3m height have been proposed, as shown in Figure 20. A total of 108,000 m^3 of rock riprap of 30-100 cm size was proposed for the rehabilitation work of the upstream slope of Pa Bon dam. The total work of 23,190 m^3 was completed by February 2019 (Figure 20).

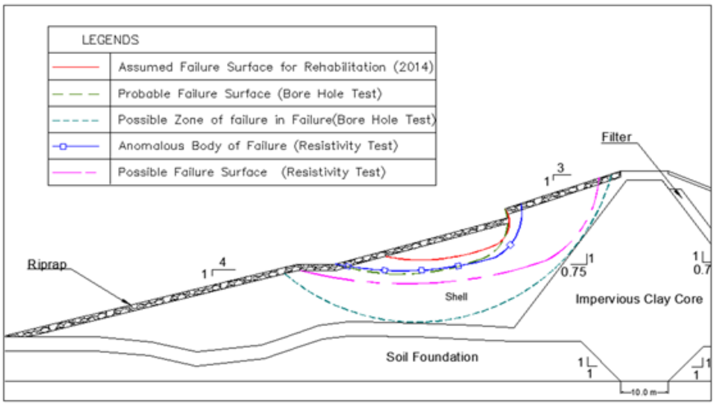
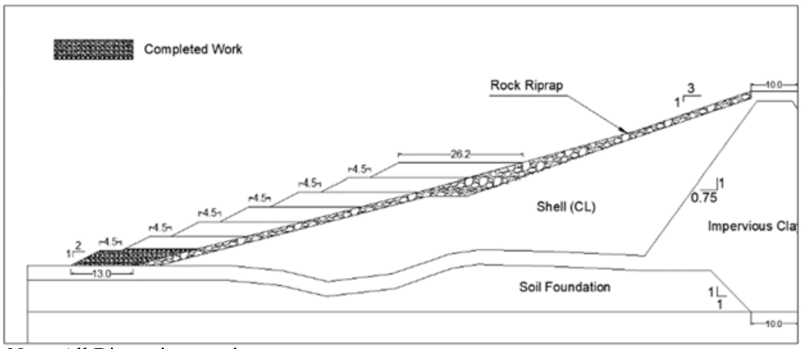


Figure (19): Failure surface determined from bore hole investigation and resistivity test



Note: All Dimensions are in m

Figure (20): Proposed rehabilitation work of Pa Bon dam (Soralump, Pien-Wej et al., 2019)

CONCLUSION

The failure surface of Pa Bon dam was estimated from various site investigation results and rehabilitation work was proposed accordingly. The investigation helped in determining the length and depth of failure surface and proposing a possible failure surface in the future, if rehabilitation work is not carried out.

Acknowledgement

The authors would like to thank Geotechnical Engineering Research and Development Centre (GERD), Kasetsart University and Royal Irrigation Department, Thailand for providing the available site investigation results.

REFERENCES

Budhu, M. (2013). "Soil mechanics and foundations". John Wiley and Sons, Inc., USA.

Calamita, G. et al. (2012). "Electrical resistivity and TDR methods for soil moisture estimation in central Italy test-sites". Journal of Hydrology, 101-112, 454-455.

Cha, M., et al. (2014). "Small-strain stiffness, shear-wave velocity and soil compressibility". Journal of Geotechnical and Geoenvironmental Engineering, 140 (10).

Clement, R., and Moreau, S. (2016). "How should an electrical resistivity tomography laboratory test cell be designed? Numerical investigation of error on electrical resistivity measurement". Journal of Applied Geophysics, 127, 45-55.

Panthi, K., and Soralump, S. (2020). "Determination of residual shear strength from reversal direct shear test: analysis and recommendation". International Journal of Recent Technology and Engineering (IJRTE), 8 (5), 6.

Park, J., et al. (2017). "Predicting anomalous zone ahead of tunnel face utilizing electrical resistivity: II. Field tests". Tunnelling and Underground Space Technology, 68, 1-10.

Ranjy Roodposhti, H., et al. (2019). "Electrical resistivity method for water content and compaction evaluation: a laboratory test on construction material". Journal of Applied Geophysics, 168, 49-58.

Shatnawi, A. (2012). "Siltation of Alghadeer Alabyadh reservoir". Jordan Journal of Civil Engineering, 6 (1), 28-38.

Shrestha, A., et al. (2019). "Determining shrinkage cracks based on the small-strain shear modulus–suction relationship". Geosciences, 9 (9).

Soralump, S., et al. (2018). "Assessment of soil using screw driving sounding (SDS) method in soft Bangkok Clay." 8th Regional Symposium on Infrastructure Development in Civil Engineering (RSID8).

Soralump, S., et al. (2019). "Cyclic drawdown of water causing the slope failure of canal and dam". 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Taipei, Taiwan.

Veselý, V., et al. (2015). "Influence of crack propagation on electrical resistivity and ultrasonic characteristics of normal concrete assessed by sequential TPB fracture test". Theoretical and Applied Fracture Mechanics, 80, 2-13.