Risk Assessment Scenario of Machap Dam Overtopping Using New PMP Malaysian Series

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ABSTRACT

A hydrological dam safety analysis was carried out for existing Machap dam (CA= 77 km^2) due to change in the extreme rainfall condition in the watershed. It is important to ensure that extreme meteorologically induced flood rises do not exceed its crest level. Step-by-step procedures were carried out in tandem to evaluate the hydrological performance of the gated spillway capacity in light of an extreme storm event of PMP/PMF magnitude.

This study adopts a newly developed "inland" type of PMPs compared to the original design PMPs. A catchment routing and reservoir procedures were then used to translate the PMPs to PMFs and estimate the outflows and corresponding flood rises over the crest level for all durations. The results of the PMPs/PMFs were comparable to the "Creager" type of catchment area-PMP relationship of various dams in Malaysia.

A conventional reservoir routing procedure by modified puls technique is then carried out for all PMP/PMF durations; i.e., 1 to 120 hours. Three (3) scenarios are performed; namely, (1) when the gates are fully closed, (2) when the gates are partially open in light of impeding PMP/PMF event and (3) when the gates are fully open. The last scenario (case 3) represents the most efficient and effective management of the reservoir gate operation as the original designer intended. The flood rises for all durations are considered lower than the embankment crest level. The results also show expectedly the failures of both cases (1 and 2) for their inadequate capacity to allow safe passage of flood water of PMP/PMF magnitude.

KEYWORDS: Dam safety, Overtopping, New inland PMP series , PMF.

INTRODUCTION

Dams have served many beneficial purposes in the water resources system and management. They are constructed to moderate the fluctuating inflows that vary in both spatial and time domains. They are theoretically and practically known to be designed for no-failure mode. Any incidents such as dam breaching by overtopping would be catastrophic to the downstream.

High velocity water, debris and mud laden torrents severely affect the downstream inhabitants. This results in immeasurable human life and economic/property losses. Specifically failure of embankment (both earthfill and rockfill) type of dams can be fatal as the erosions of the downstream face of the dam are caused by the uncontrolled overspill. The high velocity torrent toggles negative pressure or cavitation on the surface of the embankment.

DAM OVERTOPPING

Amongst the dam structural appurtenances, spillway capacity is one of the most significant factors

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attributed to the ability of a dam to pass the maximum flood (ICOLD, 2012). This maximum flood magnitude is estimated based on the probable occurrence of an extreme storm; i.e., Probable Maximum Flood (PMF) (as derived from PMPs). In other words, the dam body itself is designed such that risk of overtopping will be minimum by adopting the highest design storm and flow, also known as Spillway Design Flood (SDF).

In particular, earth and/or rock fill type of embankment dams are the most vulnerable to failure by overtopping. If the dam is being overtopped by the uncontrolled overspill, a high velocity flow field at both the crest and downstream face of the dam body is to be expected. This high velocity in turn induces cavitation at the location of negative pressure zone. As a result, this would cause erosion of the downstream face of the dam structure. On the other hand, concrete gravity and rolled compacted concrete dams are less susceptible, as they are constructed of higher strength materials compared to compacted earth and rock structures.

Spillway capacity is one of the most critical factors to be reckoned in light of an exceptional meteorological event. Its ability to pass the design floods is important to the structural integrity of the dam body. Two types of spillways are normally used in the conveyance of flood water through the reservoir water body. A free flow or non-regulated spillway is commonly used in most of the water supply purpose dams/reservoirs. On the other hand, gated or regulated spillway is a common feature for flood mitigation and hydropower purpose dams/reservoirs. The gated spillway offers advantage of increase in reservoir storage volume and available hydraulic head. The spillover from the dam is also controlled by the gates and/or other types of hydraulic control equipment. One of the disadvantages of gated spillway is that the regular and frequent operation and maintenance of the gated structures are routinely overlooked. In light of an extreme meteorological event, the gates either fail or slow to operate due to equipment malfunction.

OBJECTIVES

The objectives of this study are to:

- assess the risk of overtopping and performance of the spillway of the existing Machap dam (CA= 77 km^2) in the upper Benut and Machap river basin;
- evaluate various scenarios of radial gate operation;
- recommend, if any, the remedial measure(s)/option (s) to mitigate the deficiency in spillway capacity.

DESCRIPTION OF STUDY AREA: KLANG GATES DAM

Machap dam (CA= 77 km^2) is a dual domestic water supply and flood mitigation reservoir in the southwest region of the state of Johor. The dam is located at the headwater region of Sg. Benut on one of its major tributaries. The name of the dam is after Machap river. The catchment is bounded by 1º 53.3’ N and 103º 16.3’E.

It is an 11.5 m high earthfill embankment dam equipped with three radial gates at its crest level; +14.02 m msl. The dam crest length runs approximately 550 m at the dam embankment crest level (ECL); +19.82 m msl.

The storage volume of the reservoir at its full supply level (FSL); i.e., +15.85 m msl, is 30.5 MCM. The catchment area or lake surface area is 9.09 k m^2, slightly more than 10% of the total catchment area draining at the dam site. The design PMF is 306 m^3/s based on the outlet capacity of the spillway. Vital information on the dam is tabulated below. Figure 1 shows the location and catchment map of Machap dam.

Type of dam	**Earthfill embankment**
Height, m	11.5
Crest length, m	550
Embankment crest level ECL, m msl	+19.82
Full supply level FSL, m msl Located at the top of ungated weir	+15.85
Catchment area, km^2	77
Storage capacity, MCM at FSL	30.6
Maximum discharge, m^3/s	306
Surface area @ FSL, km^2	9.09
Hazard classification	Significant to be assessed based on PMP/PMF protocol
Spillway type	2 ungated overflow weirs, 3 radial gates
Spillway radial gates	6.1 m x 3.35 m

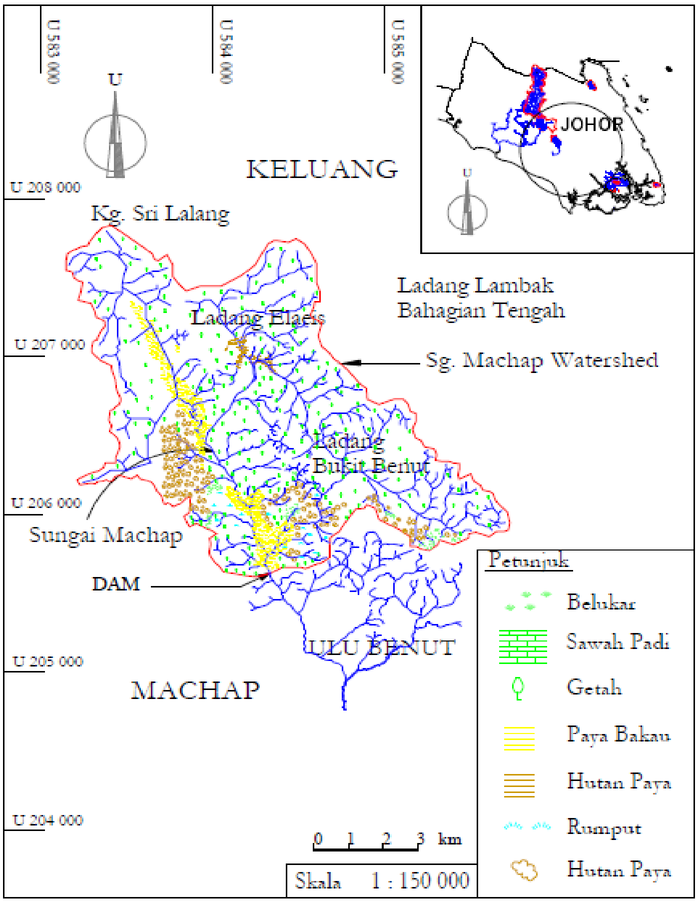


Figure 1: Location Map of Machap Dam and Its Appurtenances
Source: www.water.gov.my

METHODOLOGY OF ASSESSMENT

The methodology of assessing the hydrological dam safety primarily envisages the review of the spillway capacity and dam overtopping likelihood. The steps involved are: (1) derivation of PMPs at the project/study site, (2) translation of PMPs to PMFs/SDFs using a catchment rainfall runoff or response function model and (3) a conventional reservoir routing technique to estimate the flood rise over the dam's full supply level (FSL).

The derivation of PMPs in this study is carried out mostly by reviewing the available past studies and findings in Malaysia. The prevailing PMP convention is duly reviewed and adopted as appropriate. Catchment response and convolution lumped parameter model is used to translate PMPs to PMFs for various durations. Finally, the derived PMFs are then appropriately routed through a lumped parameter reservoir. The final results of this exercise/undertaking are to ensure that the dam is not overtopped passing its embankment crest level (ECL).

PMP DERIVATION

Probable Maximum Precipitation (PMP) represents the upper limit of the precipitation/rainfall under probable and favorable contributing factors, such as availability of moisture and other favorable meteorological conditions, absence/presence of moisture barrier such as higher mountainous range in the path of storm movement, availability of cumuli or particles that water vapors can be adhered to among others. PMP is different from other design parameters of less severity as it cannot be ascribed with a probability of occurrence or return period.

Probable Maximum Precipitation (PMP) is derived based on mostly observed maximum rainfall records with the provision of storm maximization and transposition technique in tandem (WMO, 1986, 2009). Based mostly on practical experiences in Malaysia, PMPs are derived based on the historical maximum rainfall records mostly in the east coastal regions of Peninsular Malaysia. This region is exposed to more severe storm events during monsoon season.

The observed records that were collected over the years, both recording and not recording maximum rainfalls, provide the basis of PMP derivation. Major undertakings were carried out in the Kelantan Flood Mitigation Project (SSP/SMHB,1997) and Interstate Raw Water Transfer from Pahang to Selangor (NK/SMHB, 2000). A review of past PMP studies can also be found in Desa and Rakhecha (2007), NAHRIM (2008) and Heng and Hii (2011).

In this study, for uniformity, inland PMPs derived by SMHB (2012) are adopted. There are two series of PMPs based on the geographical location of the proposed dam site; namely (1) coastal and (2) inland PMP series. The coastal series was derived earlier in the late 1970s based on observed records of long-duration storm occurrences in the eastern coastal region of peninsular Malaysia. The observed records of Mersing and Air Tawar were used. The highest rainfall records in the 1970s are not in any way exceeded with the recent studies by Atikah (2009) and NAHRIM (2009).

On the other hand, the inland series is merely a reduced version of the coastal PMP with a transposition factor to the inland region/site of the western coast of Peninsular Malaysia. In addition, the original PMPs that were adopted in the design of the dam (ACE, 1988) are also considered in this study. Table 1 summarizes the PMPs for original dam design and both coastal and inland regions of 1- to 120- hour durations.

The original short duration PMPs are slightly lower than the newly derived inland and coastal PMPs, but are comparable to long duration coastal PMPs.

PMP/PMF/SDF ROUTING

To estimate the incoming flood into a reservoir, an appropriate technique is needed to translate the PMPs into probable maximum flood (PMF). In turn, it is adopted for the spillway design of a dam.

Table 1. Coastal, Inland and USBR PMP (Short- and Long-Duration)

Duration (hour)	Coastal PMP (mm)	Inland PMP (mm)	Machap dam PMP (mm)
Short Duration PMP			
1	211	188	N/A
3	338	300	N/A
6	440	391	318
12	584	518	490
24	777	692	692
Long Duration PMP			
48	1356	908	1209
72	1593	1067	1508
120	2030	1360	1930

Adopted by SMHB (2012); Machap Dam (1988).

The procedure of the translation of Probable Maximum Flood (PMF) using Probable Maximum Precipitation (PMP) is mostly carried out using a conventional rainfall runoff routing by convoluting the generated runoff based on rainfall temporal distribution. Translating and routing by convolution of temporally distributed PMPs into PMFs of various rainstorm durations; i.e., from 1 to 120 hours form one of the important tasks in a standard PMP/PMF study. Out of many hydrological rainfall runoff techniques available, two approaches or models are the most commonly used in the local context, (1) hydrological procedure No. 11 on flood estimation (Taylor and Toh, 1976) and (2) modeling approach using proprietary as well as nonproprietary mathematical models/software. For uniformity, the former is adopted in this study.

RESERVOIR ROUTING

It is important for the outlet structures; i.e., sluice gates and spillways of a dam, that they shall be able to evacuate an extreme flood of PMP/PMF magnitude for the protection of the main dam body. Overtopping due to inadequacy of the outlet and/or spillway capacity is accountable for most of the dam failure worldwide (ICOLD, 2012). For gated spillways such as top sealed radial gates, it is advisable to fully open the gates on the onset of an impending PMP/PMF event.

Water balance description can be quantitative written in the form of flow continuity equation over a fixed domain; in this case, in a reservoir. The rate of change of storage in the reservoir water body is the summation and quantification of all inflows from various sources and appropriately deducting the amount of outflow via outlet structures, such as spillways or bottom outlets of a reservoir/dam. For simplicity, it is assumed that the bottom outlet flow and other losses such as seepage through the dam body are negligible. In addition, the reservoir is assumed at its full supply level during the beginning of a PMP/PMF event.

RESULTS AND DISCUSSION

PMP/PMF Catchment Routing

The catchment routing adopted in this study is a simple rainfall runoff modeling procedure based on Snyder type of synthetic unit hydrograph (SUH) approach. First, the estimated 10 mm unit hydrographs for various durations are derived. Major topographic and geographic characteristics such as length, area and slope of the catchment are used to derive the unit hydrographs. Conventional convolution is then performed subsequently by integrating through the entire temporal distribution of PMP. It is also assumed that due to smaller catchment size, PMPs are effective on the entire catchment area, therefore the areal reduction adjustment is not taken into consideration.

In addition, due to smaller reservoir surface area, PMPs that are falling directly onto the lake surface especially at FSL are negligible. The inland PMP/PMF hydrographs for 1- to 120-hour durations are shown in Figure 2.

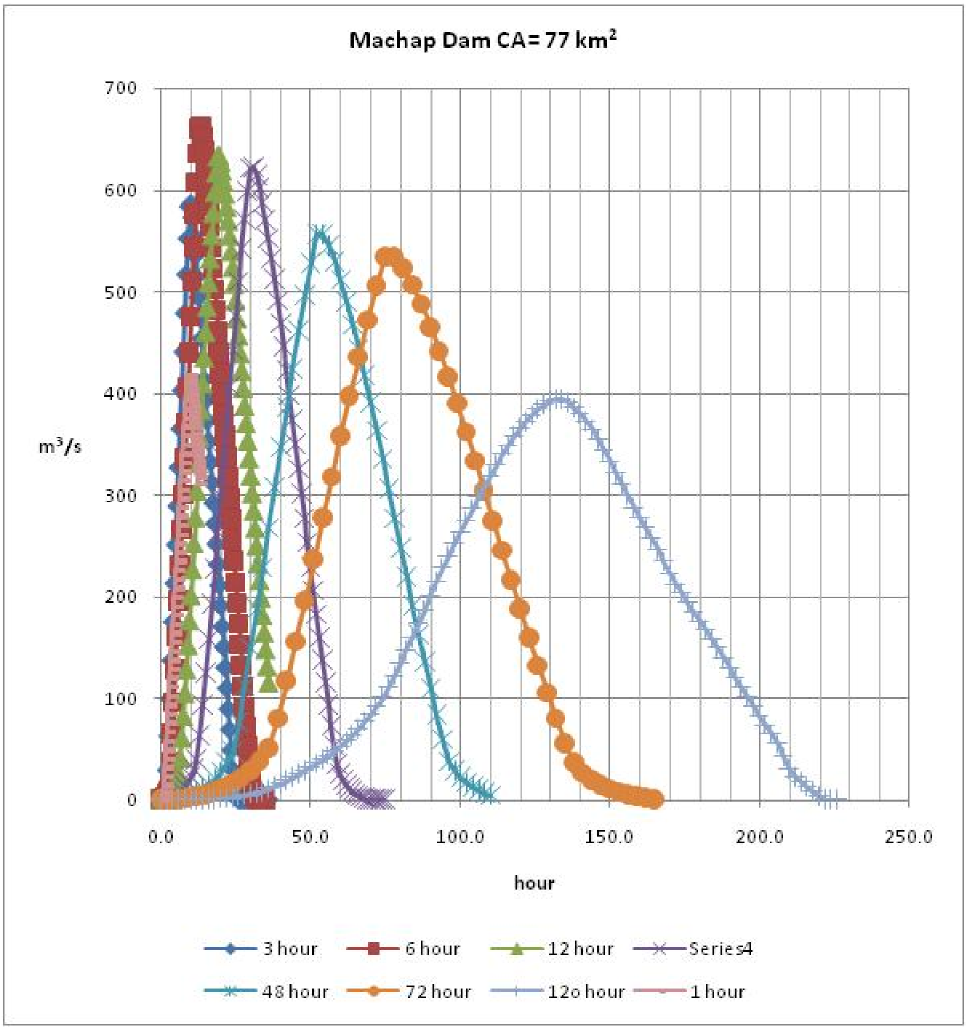


Figure 2: Inland PMP/PMF Catchment Routing: 1- to 120-Hour Durations

Reservoir Routing

The primary purpose of reservoir routing is to determine the outflows and corresponding flood rises of the PMPs/PMFs as they pass through the reservoir. It is desirable that the maximum flood rise for various durations; i.e., from 1- to 120-hour durations, is lower than the embankment crest level (ECL) of the dam, failing which runs into the risk of being overtopped.

For the routing procedure of Machap dam (CA= 77 km^2), there are three possible scenarios to be considered and carried out in tandem.

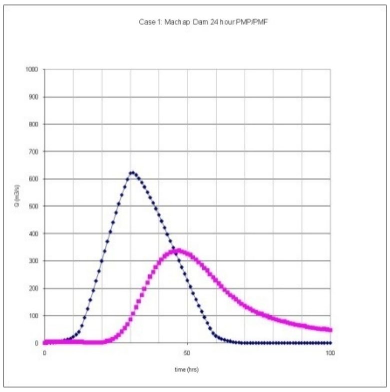
- Case I: Radial gates fail to open (worst scenario).
- Case II: Radial gates open partially 1.7 m wide.
- Case III: Radial gates open fully in anticipation of a PMP/PMF event.

Table 2. Results of PMP/PMF Reservoir Routing: 1- to 120-hour Durations

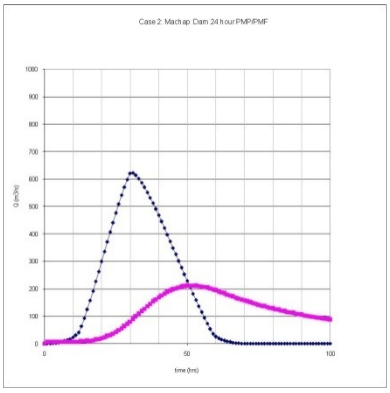
Duration (Hour)	Unit hydrograph Q	Time to peak tp	Base flow time tb	PMP	PMF	Q	Flood rise
Case 1: Overtopping of radial gate							
	m^3/s /cm	hour	hour	mm	m^3/s	m^3/s	m msl
1	20	8	21	211	417	48	18.10
3	18	8	23	338	587	118	18.90
6	16	10	27	440	662	190	19.70
12	12	13	33	584	634	237	fail
24	9	18	47	777	622	336	fail
48	5	29	74	1356	557	398	fail
72	4	39	101	1593	535	446	fail
120	3	60	154	2030	394	359	fail
Case 2: Radial gates partially open							
Duration (Hour)	**Unit hydrograph Q**	**Time to peak tp**	**Base flow time tb**	**PMP**	**PMF**	**Q**	**Flood rise**
	m^3/s /cm	hour	hour	mm	m^3/s	m^3/s	m msl
1	20	8	21	211	417	60	16.30
3	18	8	23	338	587	94	17.10
6	16	10	27	440	662	124	18.00
12	12	13	33	584	634	145	18.75
24	9	18	47	777	622	211	fail
48	5	29	74	1356	557	239	fail
72	4	39	101	1593	535	276	fail
120	3	60	154	2030	394	256	fail
Case 3: Radial gates completely open							
Duration (Hour)	**Unit hydrograph Q**	**Time to peak tp**	**Base flow time tb**	**PMP**	**PMF**	**Q**	**Flood rise**
	m^3/s /cm	hour	hour	mm	m^3/s	m^3/s	m msl
1	20	8	21	211	417	97	16.00
3	18	8	23	338	587	169	16.80
6	16	10	27	440	662	232	17.40
12	12	13	33	584	634	269	17.60
24	9	18	47	777	622	364	18.50
48	5	29	74	1356	557	410	18.81
72	4	39	101	1593	535	443	19.10
120	3	60	154	2030	394	358	18.30

FSL + 14.02 m msl @ radial gate
FSL + 15.85 m msl @ ungated spillway
ECL + 19.85 m msl

Case 1



Case 2



Case 3

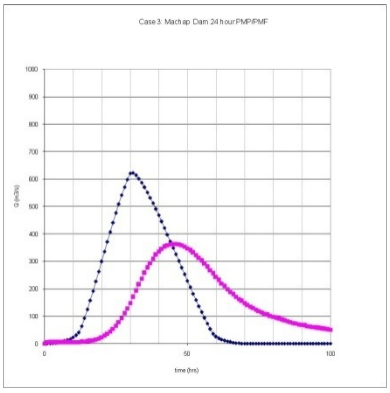


Figure 3: Machap Dam/Reservoir Routing: 24-hour Duration
(Inland PMP SMHB, 2012)

Case I

Under the worst case scenario, the radial gates fail to operate during the critical time, especially at the onset of a PMP/PMF event. Storage behind the closed gate therefore also fails to evacuate on time to make room for high inflows. This leads to the radial gates being overtopped with the fast arrival of torrential inflows of PMP/PMF magnitude. This likelihood case is not to be discounted as most of the time, due to lack of regular maintenance of the radial gates and other associated mechanical components and equipments.

The gates which are held by the trunnion pins are rendered completely inoperable even by manual cranking in this case. As a result, the PMP/PMF spills over the top of the radial gates similar to weir overflow hydraulic regime. It is also assumed that under this worst scenario, all three gates are expected to be malfunctioned during the PMP/PMF event. The expected results of this scenario would be overtopping of the dam crest at ECL; i.e., +19.82 m msl.

The flows overtop the top of the weir at +17.38 m msl. Prior to overtopping, outflows are mainly realized by the ungated weir with their sill elevation at +15.85 m msl.

Case II

Under this slight optimistic scenario, the gates are just in time to open up vertically to 1.7 m arbitrarily from sill crest level at + 14.02 m msl. The bottom of the gates is at +15.72 m msl. This is the case where the sluicing or underpassing orifice type of hydraulic flow regime is taking place. The outflow undershoots from the bottom of the radial gates toward the spillway chute downstream. The flow is estimated based on the effective height of water level from the top water level to the middle of the opening.

Raising the gates gradually leads to the scenario under Case III. Outflows commence immediately when the reservoir water level reaches +14.02 m msl and the corresponding elevation when the gates are open is +15.72 m. the outflows begin immediately when the gates are open. When the water level reaches +15.85 m, both ungated weir and sluiced flows are effective.

Case III

This is the most optimal gate operation mode. The gates are raised to fully open position just in time by prior evacuation of the impounded water behind the radial gates; i.e., about 1.83 m measured from the sill crest of the radial gate to the full supply level which coincides with the top of the ungated overflow weir.

The flow equation over weirs at both +14.02 m and +15.85 m msl is similar to the conventional weir flow equation. It is assumed that all three radial gates are open during the impending PMP/PMF event.

CONCLUSIONS

A hydrological dam safety exercise is carried out with the objective to assess the performance of spillway gallery fitted with three radial gates and two ungated weirs in light of an extreme meteorological event of the PMP/PMF magnitude.

Machap dam (CA= 77 km^2) is a dual flood mitigation and water supply reservoir under the auspice of Jabatan Pengairan dan Saliran (JPS) in the southwestern region of the state of Johor.

This study adopts "coastal" type of PMPs as derived previously by SMHB (2012) based on close proximity of the dam catchment and the rainfall stations, where the historical maximum rainfall records are adopted in the PMP derivation. A catchment routing procedure is used to translate the PMPs to PMFs for 1- to 120-hour durations. The results of the PMPs/PMFs are comparable to the "Creager" type of catchment area-PMP relationship of various dams in Malaysia.

A conventional reservoir routing procedure by modified puls technique is then carried out for all PMP/PMF durations; i.e., 1- to 120-hour durations. Three scenarios are performed; namely: (1) when the gates are fully closed, (2) when the gates are partially open in light of impeding PMP/PMF event and (3) when the gates are fully open. The last scenario (case3) represents the most efficient and effective management of the reservoir gate operation as the original designer intended. The flood rises for all durations are considered lower than the embankment crest level.

The results also expectedly show the failures of both cases 1 and 2 for their inadequate capacity to allow safe passage of flood water of PMP/PMF magnitude.

REFERENCES

ACE. 1988. Machap Dam First Periodic Inspection Report, JPS, Government of Malaysia.

Australia Bureau of Meteorology. 2003. The Estimation of Probable Maximum Precipitation in Australia: Generalized Short-Duration Method, Bureau of Meteorology, Melbourne, Australia.

Chow, V.T., Maidment, D.R. and Mays, L. 1988. Applied Hydrology. McGraw Hill, New York.

Desa, M.N. and Rakhecha, P.R. 2007. Probable Maximum Precipitation for 24-h Duration over an Equatorial Region: Part 2-Johor, Malaysia. *Atmospheric Research*, 84 (1): 84-90.

Heng, H.H. and Hii, C.P. 2011. A Review on PMP Estimation in Malaysia. *Int. Jour. Hydrology Science and Technology*, 1 (1/2): 63-87.

NAHRIM. 2008. Derivation of Probable Maximum Precipitation for Design Floods in Malaysia. Technical Research Publication (TRP) No. 1, Ministry of Natural Resources and Environment, Kuala Lumpur, Malaysia.

NK/SMHB. 2000. Nippon Koei in Association with SMHB. Pahang- Selangor Raw Water Transfer Project Engineering Services and Detailed Engineering Design: Hydrograph, Final Report. Malaysia, JBA, JKR.

SMHB/RB/JPZ. 2000. National Water Resources Study 2000-2050. Economic Planning Unit, Government of Malaysia.

SSP/SMHB. 1997. Kelantan River Flood Mitigation Project: Feasibility Study. Jabatan Pengairan dan Saliran, Kuala Lumpur, Malaysia.

Taylor, M.A.W and Toh, Y.K. 1976. Design Flood Hydrograph Estimation for Rural Catchments in Peninsular Malaysia. Kuala Lumpur, Hydrological Procedure No. 11. Jabatan Pengaliran dan Saliran, Ministry of Agriculture, Malaysia.

WMO. 2009. Manual on Estimation of Probable Maximum Precipitation. Operational Hydrology Report No. 1045, World Meteorological Organization, Geneva.

www.smhb.com

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