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DAM BREAK EVENT MODELLING AND CASE STUDY: A CORRELATIONSHIP BETWEEN BREACH DISCHARGES AND DAM PHYSICAL PARAMETERS IN MALAYSIA

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Highlights:

- Maximum breach discharges to dam physical parameters (height and storage volume) and hydrological factors (PMP/PMF).

- Regression analysis and comparisons with existing empirical formulas show consistent results, supporting DF as a predictive tool for future dam break assessments.

Abstract: Dam break incident is an extreme rare event, but the impact could be potentially devastating with losses of human lives and property damages along the torrential flow path of a river basin. This paper correlates the estimated maximum dam breach discharges with the hydrological parameters such as probable maximum precipitation/flood (PMP/PMF) and other dam's physical parameters in Malaysia. The empirical results and other associated parameters of fourteen dam break studies in Malaysia were adopted in this study. Two critical and important dam physical parameters, i.e. the height or elevation and the volume of storage behind the dam are found directly proportionate to the magnitude of discharges during dam breaching events. The aggregate product of these two physical parameters is termed as dam factor (DF). These physically based parameters were also indirectly related to the duration of the time of failure and the final breach width. A regression analysis was carried out to correlate the breach discharge and DF for various dam break studies in Malaysia. The prediction of the final breach width and time of failure could also be used as a first hand basis for other dam break study. Comparisons of dam breach discharges were also made using various selective equations empirically developed in the literature. The results were mostly consistent and agreeable to 14 dam case studies in Malaysia.

Keywords: dam breach; dam factor; PMP/PMF; regression

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1. Introduction

Dam break is an extremely rare event especially for existing dams built over the last fifty years or so with stringent design standard and construction protocol under the aegis of ICOLD and other regulating bodies. The dam structures have been strictly designed based on sound fundamental understandings and in depth knowledge of basic science and engineering, such as involving the multi-disciplinary fields of meteorology, hydrology, geomorphology, and geo-mechanics, construction techniques, safety and health guideline. Therefore, these concerted efforts are necessary to lower the chances of failure, which are fairly remote and at a very low probability of occurrence.

Despite the stringent rules in design standard, a subsequent dam break study is normally carried out for emergency preparedness in light of an unfortunate event. The dam break study in tandem encompasses (1) estimating the breach discharges in the event of dam break, (2) routing of the breach discharges to the downstream locations of interest using conventional flood routing techniques and (3) estimating the flood levels due to breach event at various locations of interest. The breach discharge is an extraordinarily high outflow burst if compared to both conventional 100-year flood discharges and even a probable maximum precipitation/flood (PMP/PMF) flood discharges. The additional outcome obtained specifically on the downstream flood level/stage and the critical time of flood wave arrival. These parameters are subsequently used for the preparation of a dam specific emergency action plan (EAP).

By the definition stipulated in ICOLD classification, a category A dam (>15 m high and >1.0 million cubic meter (MCM) of total storage volume) can expect a full or partial breaching failure and this can lead to potential human fatality and property losses to townships, villages, and other population centre downstream. Many existing dams in Malaysia are falling into this classification. However based on Malaysia own standard, MyDams (2017) adopts a much more conservative approach. A recommended dam safety management practices for existing and future dams in Malaysia that are limited to 10 m or more in height and storage capacity of 20,000 m^3 or more, which have a storage capacity of 50,000 m^3 or more and higher than 5 m.

Majority of the dams in Malaysia are in this grouping by exclusively either the dam height or storage capacity. Malaysia's Department of Environment (DOE)'s condition of approval for dam construction requires a comprehensive dam break analysis for downstream flood impact is to be undertaken as part of the imposed condition and requirement in Environmental Impact Assessment (EIA) study.

The results of dam break study also further lead to potential impact assessment at the downstream riparian stakeholders, more importantly the inhabitants that live along or nearby the both sides of the river bank. In addition to this, the outcomes on flood inundation will be used as primary reference for preparation of EAP. In other words, this study is specifically tailored to the dam's downstream flooding emergency preparedness effort by various agencies.

1.1. Problem Statement: Malaysia Case Study

The dam break task is somewhat different from the conventional flood assessment where in the latter undertaking, both the hydrological and hydraulic parameterizations and output can be inferred statistically from observed hydrometric records via appropriate sequences of calibration and validation processes. On the other hand, by nature, the severity of a dam break event could be several orders of magnitude higher to be reckoned with. It would be difficult to perform and carry out an in depth and thorough analysis similar to a conventional flood study.

Poor understanding of the dam failure mechanism and lack of documentation are in fact primarily attributed to mostly unavailability of systematic observed database worldwide nor in Malaysia as well. Incidents of any serious dam break incident or even of a lesser severity, such as even a minor partial breach and overtopping, has not been taken place in Malaysia. Lack of both observed records and experiences, therefore makes the dam break analysis an equally difficult and complicated task to undertake. Although aspiring with a very best concerted effort, it is however only to be empirically benchmarked on mostly hypothetical scenarios. As such, the results obtained in this study are basically a reflection of a remotely probable catastrophic event that might not even occurred but it is necessary to predict the torrential outflow due to breach and other pertinent information along the flood flow path for the preparation of an emergency evacuation plan.

There are analytical techniques available on the prediction of dam breach flow (Singh, 1996). However, most of the practical dam break studies carried out over the years since 1980's are mostly based on mathematical or numerical simulation approach (Sidek, *et al.*, 2001; Tingsanchali and Chinnarasri, 2001; Yang, *et al.*, 2007; Jeong, *et al.*, 2012; Samir, *et al.*, 2011; Xiong, 2011; Zainab, *et al.*, 2015; Hashim *et al.*, 2024). Due to the advent of fast speed computing prowess, almost all dam breach models are readily incorporated in a hydraulic river network model such as in the commercial and proprietary packages of DHI MIKE suite, Infowork and HEC RAS of USACE, USA. By doing so, this enables fairly quick assessment and prediction of the time of breach, the magnitude and temporal distribution of the hydrograph, and the lead time of wave arrival at the downstream by routing the hydrographs along the river network (Vischer and Hager, 1998).

1.2. Reasons of Dam Failure

Dam failures can result from any one, or a combination of the causes. Sometimes a small but vital forewarning sign might perhaps sound an alarm on the impending danger of breach to be taken place in the near future. Unfortunately these oversights, negligence, or lack of concerns of these minor issues might be sidelined. Unfortunately, these factors might at a later time trigger the onset of the dam breach event.

Inadequacy of the spillway capacity, i.e. design flow (DF) over spillway structure adopted during the detail design stage, that resulting in uncontrolled overspills over the downslope embankment of the dam structure. The negative pressure induced on the downstream surface of the dam body exerts negative pressure and eventually leads to uncontrolled high intensity erosion. Moreover, internal erosion of fine soil out of dam body, or also known as piping that leads to gradual loss of fine particles through the dam embankment. This type of failure might be attributed to a variety of reasons, such as faulty construction technique, lack of compaction during construction stage, animal burrowing and deep tree root or macropore intrusion into the inner core of the dam body or a foundation leakage.

The most frequent dam failure mode (accounted for about 70%) is the excessive upper catchment flooding that primarily leads to dam overtopping. If the spillway capacity is inadequate to facilitate safe passage of these torrential floodwaters, the uncontrolled overtopping over the embankment will erode the downstream dam structure and leads to dam ingress or head-cutting proceeding to full collapse within a shorter time frame. The second most frequent failure mode is by the adverse action of internal erosion or piping failure, which accounts for about 15% in total. This mode of failure is mostly gradual in terms of time scale, i.e. taking a longer period of time for a small interconnected erosion or piping to full breach. Other modes of failure, accounting for remaining 15% are mainly minor and incidental. The worldwide dam failure statistics (FEMA, 2013) also mentions that the probability of failure is much greater for earth- or rock-fill type of embankment than for concrete and masonry type of dam structures.

Most of the dam breach event takes place over a long duration of time period, with the exception of sudden freak events, such as extreme storm events or acts of war. **Table 1** shows the dam failure statistics from 1957 to 2011 for the documented cases of dam failure (FEMA, 2013). **Table 2** shows a partial list of major dam failures and their primary causes and reasons in the 20th and 21st centuries from "Partial list of dam failure worldwide," 2013.

Table 1. Dam failure incidents 1957-2011

Cause of failure	Number of dam failure	Percentage of dam failure %
Overtopping	465	70.9
Piping	94	14.3
Structural	12	1.8
Human related	4	0.6
Animal activities	7	1.1
Spillway	11	1.7
Erosion/slide/instability	13	2.0
Unknown	32	4.9
Others	18	2.7

Table 2. Partial list of dam failure and main reasons

Dam/reservoir	Location	Type	Year	Reason of failure	Death toll/cost
Situ Gintung	Indonesia	Earth	2009	Piping/ Overtopping	100 dead, 400 home
Taum Sauk	USA	Concrete	2005	Overtopping	Damage avoided
Big Bay	USA	Earth	2004	n/a	100 homes
Shi Kang	Taiwan	Concrete	1999	Earthquake	Gates damaged due to uneven settlement
Folsom	USA	Concrete	1995	Spillway gate	Damage avoided
Val di Stava	Italy	Earth	1985	Improper construction	268 people 155 million Euro
Tous	Spain	Rockfill	1982	Spillway	20 people
Morvi River	India	Earth	1979	Spillway	15,000 people
Laurel Run	USA	Earth	1977	Overtopping	40 people 5.3 million USD
Kelly Barnes	USA	Earth	1977	Piping	39 people 2.5 million USD
Teton	USA	Earth	1976	Foundation	14 people/1 Billion USD
Ban qiao and series of smaller dams	China	Earth	1975	Overtopping	Approximately 200,000 people
Balwin Hills	USA	Earth	1976	Ground movement	5 people
Malpasset	France	Arch	1969	Overtopping/ Foundation failure	450 people
Vaiont	Italy	Arch	1963	Landslide/ Overtopping	2500 people

St. Francis	USA	Arch	1928	Foundation failure	450 people
Austin	USA	Arch	1911	Foundation failure	87 people

1.3. Objective

The objectives of this study are: (1) identifying the critical parameters (water level and storage capacity during the onset of a dam breaching event) and gaining insight on their roles to triggering dam break scenario such as quantification of the breach hydrograph, and (2) correlating the dam breach discharges and relevant physical parameters of dam break studies carried out in Malaysia.

2. Literature Review

This review presents the results of dam break studies carried out in Malaysia based on the earlier works and findings of United States of Bureau Reclamation (USBR) and National Oceanic and Atmospheric Administration (NOAA) (Walder and O’Connor, 1997). Due to hypothetical nature of dam break event, almost all the results presented were based on mathematical modelling approaches. The actual dam break events are remotely rare other than a few actual events that are well documented in the literature (NWS, 1988; ICOLD, 1995; Singh, 1996; Vischer and Hager, 1998; Zagonjolli, 2007, HEC, 2014, Zhang, *et al.*, 2016). These information were adopted in parameter derivation for respective computer models. From the empirical observation of these rare events worldwide, the breach in terms of quantifiable outflow at the dam site is strongly correlated with some of the prominent physical geometric parameters of the dam structure and the prevailing hydro-meteorological setting and also hydrological phenomenon in the upper catchment of the dam, such as the height of the embankment structure and the volume of water impounded behind the dam. The extreme meteorological event of excessive flow also leads to the basis of overtopping mechanism (mainly precipitation, or storm rainfall that proportionately induces much higher runoff) upstream of the dam site.

The flood discharges attributed to this extraordinary event are different from the conventional 100-year return period or a 1% probability of exceedance flood. It can be an event of several folds of the conventional 100-year flood. Normally, this magnitude of the flood is mostly represented by extreme hydrological regime of PMP/PMF calibre. It is normally acceptable to assume that the dam breach discharges would be several order of magnitude higher than the PMP/PMF related flood discharge. It can be expressed in terms of quotient of dam breach discharge over the corresponding PMP/PMF flood. Once the dam's structural integrity is being compromised, the breach generates torrential waves immediately downstream of the dam site. Two (2) physical parameters, the height or elevation and the volume of storage behind the dam are found to be directly influencing the magnitude of outflow aftermath of a dam breaching event. In addition, temporal factor such as the time elapsed from the initiation to breach completion is also important. Shorter time denotes a fast response with a relatively higher breach discharge. In most of the computer model, several essential parameters such as slope formation in terms of vertical to horizontal angle, the initial and bottom water level, and the final or terminal breach width are also specified a priori.

Fundamental mechanisms of a dam break modelling approaches are well explained by prominent researchers and organizations such as USBR and NOAA. One of the most prominent and widely used model parameterization in the USA and also worldwide is FLDWAV, DWOPER and its variants by NOAA (NWS, 1998; Sylvestre and Sylvestre, 2013). The dam break modelling approach has also been an add-on subroutine to some flood plain river hydraulic modelling suites/packages, such as BOSS-FLDWAV, MIKE11 of Danish Hydraulic Institute (DHI), HEC-RAS 4.10 and its recent 2-D version of HEC (USACE), INFOWORK-RS of Wallingford HR Group, to mention a few. These mathematical models are also being adopted in most of the dam break assignments in Malaysia.

The actual dam break events are rare even in worldwide perspective and at least to say, there is no such accident has taken place in Malaysia although there are more than one hundred dams/reservoirs in Malaysia. Therefore, only a handful actual events that are been well documented such as in ICOLD (1995), NWS (1998) and Singh (1996). As of today, there is no fatal dam break incidents occurred in Malaysia. The exception was a minor gold mines tailing dam breach incident in Bentong, Pahang in the mid 1980's. The information on the breach was in anyway scanty. However, no casualty was allegedly reported but the river bed downstream of the failed tailing dam structure was raised by about 1 m due to heavy flux of sediment outflow. This altered significantly the discharge rating curve of the river gauging operation downstream. From many observed breach events, the characteristic of the structural dam breach varies with some of the physical geometric parameters of the dam structure, such as the height of embankment structure and the volume of water impounded behind the dam. The magnitude of flood discharge during dam breach event generates torrential waves immediately downstream of the dam.

These two important parameters, the height or elevation and the volume of storage behind the dam directly influence the magnitude of outflow aftermath of a dam breaching event. In a step further, these physically based parameters were also regressed against the ultimate time of failure and the final breach width. These parametric approaches were well documented and investigated in numerous literature review and the parameters are easily obtainable as they are related to the hydraulic and geometrical properties of the dam structure, such as the volume of storage behind the dam and height of the dam structure.

On the other hand, there are also physically based mechanistic approaches where the breach of the dam structure is highly dependent on the material composition of the dam structure itself. The prediction of the breach characteristic, i.e. size, shape, and time of formation and the breach flood hydrograph is strongly dependent on the soil material properties of D50 size, dry and wet unit weight, friction or repose angle, cohesive strength and percentage of the core material, normally made of material such as, clay. A dam break failure normally consists of overtopping and internal piping/erosion of embankment materials. Only in the process based mechanistic model where these two breach phenomena are treated separately. A classification of model type by Wahl (1998) refines broadly into four (4) classes of dam breach models by various researchers. Some of these techniques are nevertheless simple to comprehend with the exception of the first and second approaches. All these techniques rely heavily on empiricism, i.e. actual dam breach records and case studies for comparison and to a limited extent. Nevertheless, verification processes in the standard protocol of conventional flood modelling exercise will be difficult to carry out. This comparison is carried out by relying on a wealth of publication and documentation of the past dam break incidents in a worldwide database (ICOLD, 1995).

3. Methodology

There are merely a handful of dam break simulation studies carried out in Malaysia. The information collected in this study by aptly gathering the basic information available in the dam break studies. Information from these fourteen (14) local dam break studies were duly compiled and arranged in two major groupings , in terms of both physical parameters, i.e. dam height, storage capacity, catchment area, hydrological parameters probable maximum precipitation/flood (PMP/PMF), and breach discharges. These information and database of the respective dams are collaged from various past studies made available via public domain. The dams are of various storage capacities from a very small capacity of about a few hundred thousand cubic meter to some 16,000 MCM. **Table 3** shows a brief description of fourteen (14) dams mainly with hydrological parameters such as breach discharges and PMP/PMF adopted in this study. On the other hand, **Table 4** shows the additional dam physical parameters such as dam height and storage capacity, which the products are to be corelated with other hydrological parameters. It is assumed that prior to the dam breach incident, the effective dam water level is at its maximum or full supply level (FSL) and the storage capacity is also assumed to be at its full capacity. This expects to result in maximum breach discharge. The literature review also identifies that both the water level and the storage capacity are positively related to higher breaching discharge.

Table 3. Breach discharge estimation of past studies in Malaysia

Dam	Breach Q outflow m^3/s	Breach Ratio PMF/Breach Q ND
Pedu, Ahning, and Muda dams, Kedah	Pedu: 15658 Ahning: 60537 Muda: 35157	6 32 4
Durian Tunggal dam, Melaka	14557	23
Saddle Dam A, Kenyir reservoir, Terengganu	PMF: 208543 CDF: 152130	11 8
Kahang Dam, Johor	PMF(1):6636 PMF(2):12356 CDF:4813	11 21 8
Kinta dam, Perak	PMF: 73000 CDF: 71000	32 31
Labuan Island Dams **Bukit Kuda Dam** **Kerupang Dam** **Pagar Dam**	 PMF: 2979 CDF: 2074 PMF: 399 CDF: 299 PMF: 1157 CDF:1075	 11/8 3/2.5 8/7
Seluyut Dam, Johor	PMF: 5424	11
Kelau Dam, Pahang	PMF:16982 CDF:16311	4 4
Bekok Dam, Johor	PMF: 3000, storage of 70 MCM PMF: 13760, storage of 610 MCM	>1 6
Jernih Dam, Melaka	PMF: 3728 CDF: 3761	49 49

PMF: Overtopping Failure; CDF: Clear Day Failure; SDF: Sunny Day Failure, ND: Non Dimensional

Table 4. Result summary of breach discharge of 14 dams

Name	Catchment area	Breach Q	PMF	Dam Height	Storage Capacity	Dam factor	Remark
	km^2	m^3/s	m^3/s	m	MCM	m-MCM	
Pedu	171	15658	2610	61	275	16775	Unspecified
Ahning	120	60537	1892	74	1080	79920	Unspecified
Muda	984	35157	8789	37	154	5698	Unspecified
Durian Tunggal	41	14557	633	26	33	858	Unspecified
Kenyir saddle dam	2600	208543	18958	155	13600	2108000	Unspecified
	2600	152130	19016	155	13600	2108000	Overtopping
Kahang	56	6636	503	6	29	174	Piping
	56	12356	588	6	29	174	Overtopping
	56	4813	602	6	29	174	Piping
Kinta	148	73000	2281	90	30	2700	Overtopping
	148	71000	2290	90	30	2700	Piping
Bukit Kuda	2	2979	271	17	4	68	Overtopping
	2	2074	259	17	4	68	Piping
Kerupang	0.2	399	133	12	0.2	2.4	Overtopping
	0.2	299	120	12	0.2	2.4	Piping
Pagar	0.5	1157	145	18	0.34	6.12	Overtopping
	0.5	1075	154	18	0.34	6.12	Piping
Seluyut	54	5424	493	30	78	2340	Overtopping
Kelau	331	16982	4246	25	137	3425	Overtopping
	331	16311	4078	25	137	3425	Piping
Bekok	360	12760	2075	20	610	12200	Piping
Jernih	3.4	3728	76	25	14	350	Overtopping
	3.4	3761	77	25	14	350	Piping

3.1. Dam Break Mechanisms

United States of Bureau Reclamation (USBR) and National Oceanic and Atmospheric Administration (NOAA) and other European Union (EU) bodies are the pioneers by their long term comprehensive and methodological studies on the modus operandi of dam break mechanism. Subsequently by taking into advantages of the efficacy and efficiency of computational power, the dam break mechanism has been simulated mathematically using various hydrogical and topographical modelling approaches. The specific study is also conveniently coupled with the numerical hydraulic flood wave routing modules in the river basin network model and simulation. Since then, a wealth of knowledge and understandings has also been accumulated as a result of their efforts, notwithstanding the observed records on actual dam break event are fewer to come by. Even a collaboration with the global database is also scarce as there are not many dam break incidents worldwide since 1950's or majority of failure incidents were just not simply reported by eyewitnesses' accounts and post incident studies.

A vast global empirical database of collected post dam break incidents unequivocally suggested that both the dam height and storage volume, and also perhaps to an extent, other pertinent physical dam features and parameters such as the shape of the breach section are also significant and instrumental in triggering a dam breach event. This inherent physically based mechanism can be safely assumed to be universal and, as such, it can be transposed with much higher certainty and confidence to any part of the globe. In general, there are two (2) major types of dam breaching mechanisms which are readily identified as the observed modes of failure, i.e. (a) overtopping, and (b) internal piping or erosion.

These two (2) major types of dam breaching mechanism account for a total of 70% of the dam failure mode (ICOLD, 1995; Singh, 1996; Rahimah, 2011; A Razak, *et al.*, 2013; FEMA, 2013). Other minor failure modes are i.e. foundation failure, wave surge, landmass slips into the reservoir volume, which in turn causes major torrential wave overtopping of the dam structures such as in the well documented case of Vaiont dam (Italy) in 1967.

3.2. Dam Failure Mechanism

3.2.1. Overtopping Failure

Overtopping failure is normally encountered during an exceptionally intense meteorological event such as extreme storm event approaching or surpassing the design parameters. Conventional hydrological design parameters are based on PMP/PMF approach and protocol. This type of failure is normally prevailed in earth or rock fill dam structure, where a headcutting erosion process will first develop in the dam embankment body and eventually by cutting into the head region through material and structural erosion. Other events that might also trigger overtopping failures are such as the extremely violent wind induced wave action over the surface of the reservoir water body. Nevertheless the secondary chances of occurrence are fairly remote compared to other failure mechanisms. These wave actions could be the triggering results of a massive landslide that generates a very high wave traversing at a fast speed toward the dam body. One particularly important and well documented event of such example of overtopping from wave incident occurred at currently defunct Vaoint dam in Italy. The dam was one of the highest dams in Europe at that time. The 1967 incident caused a massive flood wave surge downstream and fatally led to some 2000 lives perished and properties in various towns and villages along the flood path downstream suffered as well. The dam structure however remains intact and did not fail in the physical sense as it was a sturdy arch concrete dam structure that can withstand the blunt forces imparted by the raging torrential flows.

3.2.2. Internal Erosion or Piping Failure

The internal erosion or piping failure accounts for second major dam failures worldwide. Hence, very few piping failures had been well documented in such a manner for inference of the rate of breach formation for specific purpose of dam break modelling. This mode of failure modelling endeavour is always associated with the clear day or sunny day failure (CDF or SDF) scenario in dam break modelling undertakings. One of the well documented internal erosion or piping failures was Teton dam (Idaho, USA) in 1976. The dam crumbled on the fateful day of 5 June 1975 during the first refilling and impounding period by ultimately releasing some 308 MCM of reservoir storage within a few hours. The peak breach discharge reached up to 28,300 m^3/s. Prior to complete breach of the dam, a sand boil and seepage were long noticeable at about 30 m below the top embankment crest of the dam.

4. Results and Discussion

Only few dam break analyses could be obtained via public domain. This is understandable that the public dissemination of the dam failure could create unwarranted fears and anxieties to the public. It would be directly perceived and implied imminent failure could occur in the near future. Therefore efforts to carry out meaningful comparison of local dam break assignments was therefore fairly difficult and facing challenge of sufficient information acquisition. Although the results of dam breach undertaking are mostly hypothetical, this would nevertheless cause undue angsts to the general public that mostly have absolutely no knowledge on the chances of remoteness of a dam breach incident would ever occur.

The recent dam design engineering standard and protocol are based on a stringent criteria and probability to minimize the risks of dam failures. Nevertheless, most of the results and outcomes of dam breach simulation and studies were basically kept in privy and did not fully made to or communicated in unequivocal terms to the general public or to the engineering communities and peers.

Despite of this deficiency with few database at hand, compilation of necessary parameters as postulated in this study can be readily acquired. In some of the local dam break studies, there were distinction on the type of breach and mode. For example some dams were simulated under both CDF or SDF or PMP/PMF induced overtopping mechanisms as appropriate. It was normally assumed that CDF/SDF was the result of internal erosion and piping mode of failure. In addition, due to a lack of data set and other pertinent information on dam break analysis undertakings in Malaysia, a rigorous statistical co-relationship with dam height and volume of reservoir storage, other parameters therefore appeared to be less meaningful.

4.1. PMP/PMF & Dam Breach Discharge: A Comparison

The PMP/PMF floods were extracted for each dam break study accordingly. They were duly compared to a simple version of "Creager" type of enveloping regressed curve developed in Malaysia. **Figure 1** shows the plotted curve with corresponding dam catchment areas and the PMP/PMF flood discharges in abscissa and ordinate respectively (Heng *et al.*, 2013). This curve was prepared based on PMPs/PMFs records of existing and planning dams in both Malaysia and Indonesia. The regression also explained 78.6% of the data variability in the statistical analysis. The superimposed PMP/PMF of fourteen (14) dams considered in this study were comparable and consistently fall within a range of a factor of two. **Figure 2** shows the graphical plot of catchment area and the PMP/PMF and dam breach discharge of respective dams. It was normally sufficed to reckon that the dam breach discharges were somewhat higher than the PMP/PMF induced flood by several order of magnitudes. For this case, the quotient ranges from slightly more than unity to about 49 times.

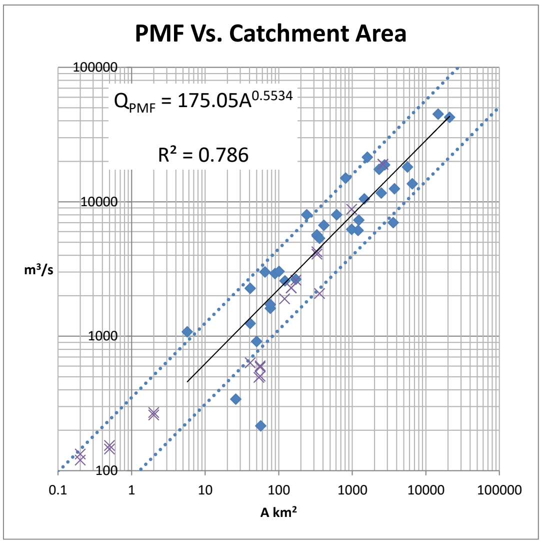


Figure 1. PMP/PMF and catchment area relationship (Dotted line: factor of 2 line for upper and lower limit, diamond: Malaysia and Indonesia PMP/PMFs; Cross: 14 dam PMPs/PMFs) (Heng *et al.*, 2013)

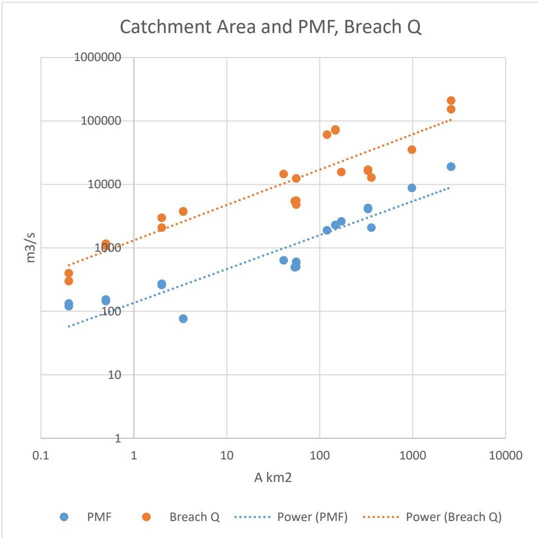


Figure 2. Catchment area, PMF, and breach Q relationship

4.2. Dam Breach Discharge and Dam Factor Relationship

As mentioned earlier, two (2) dam physical parameters, i.e. the height or elevation and the volume of storage behind the dam are directly affecting the magnitude of dam breach outflow. The product of these two parameters is termed as dam factor (DF) in this study. These physically based parameters were also directly proportional to the duration of the time of failure and the final breach width. A regression analysis was then carried out to correlate the breach discharges and DFs. A regression correlation coefficient of 0.84 indicated a fair fitting of the data set. **Figure 3** shows the results of nonlinear regression analysis by a best fit curve through the data set of breach discharges and their corresponding dam factors.

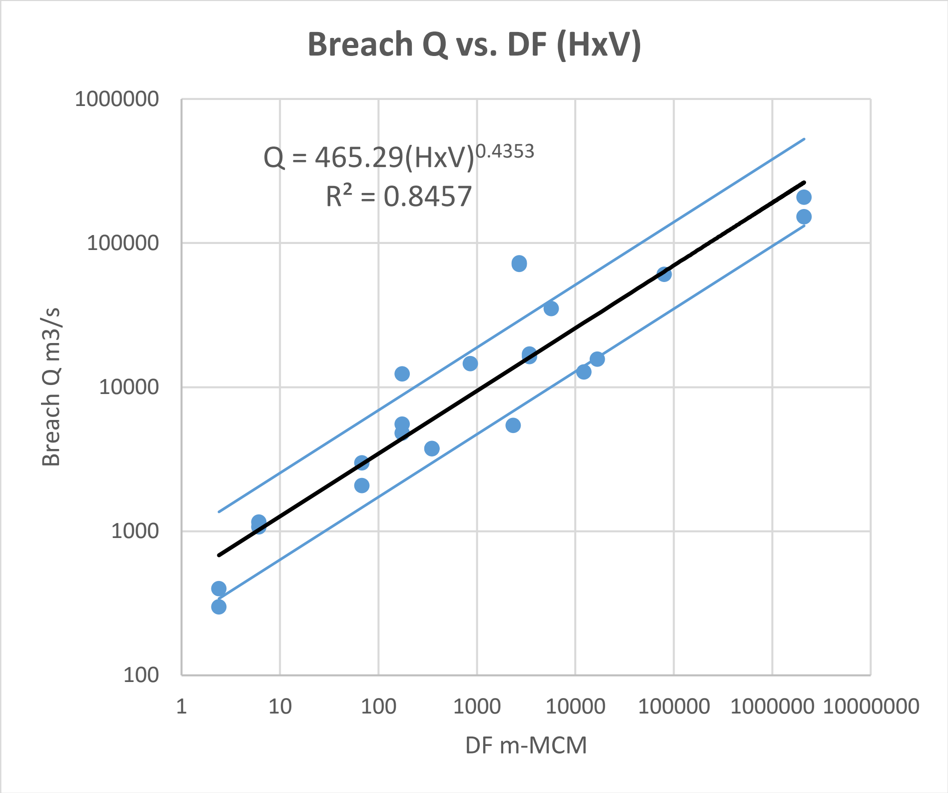
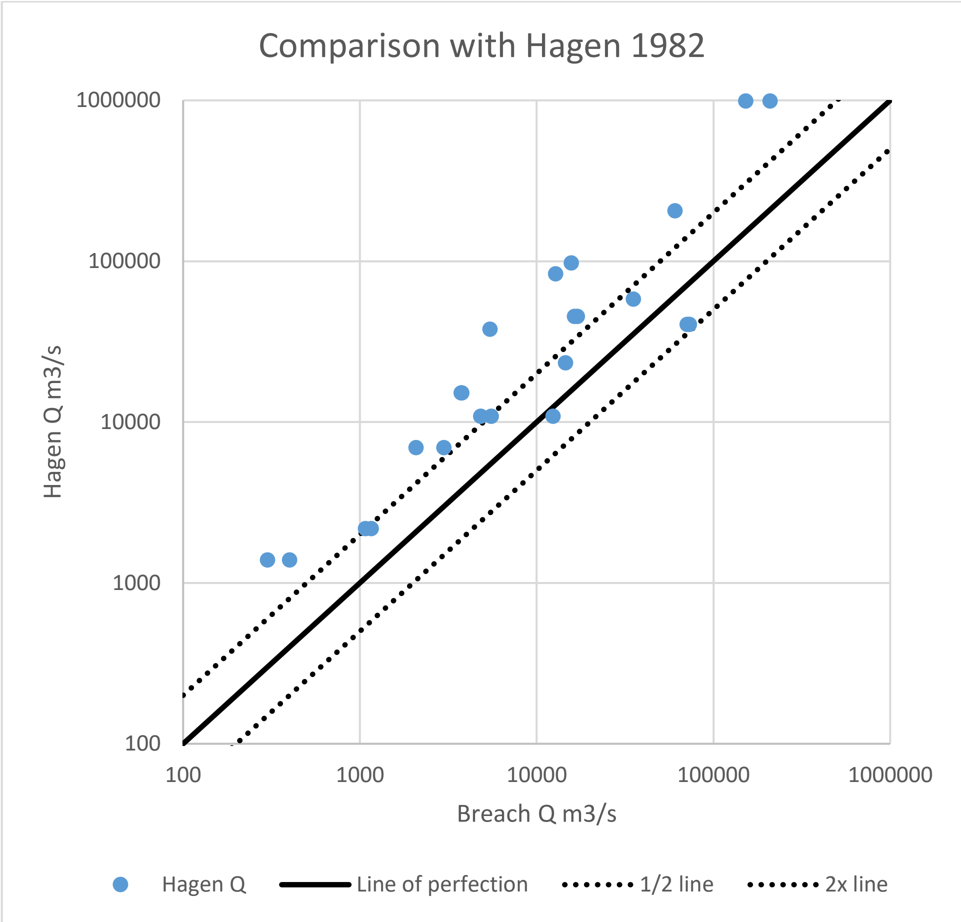


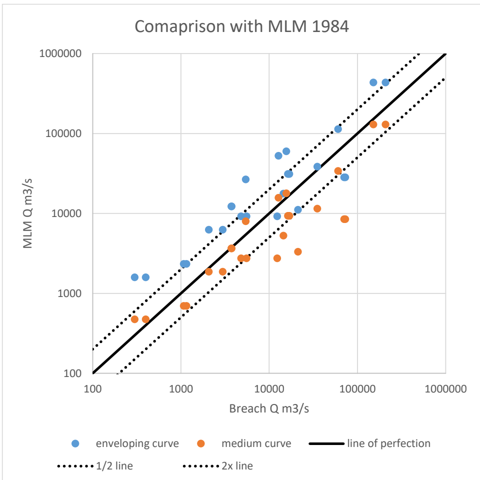
Figure 3. Breach discharge and product of height and storage capacity (Dam Factor/DF) relationship (Dam factor DF – Product of Height (H) and Storage Volume (V). Lower and upper lines are the minimum and maximum bound, corresponding to 50% and 100% of the middle regressed 1:1 perfect line of relationship)

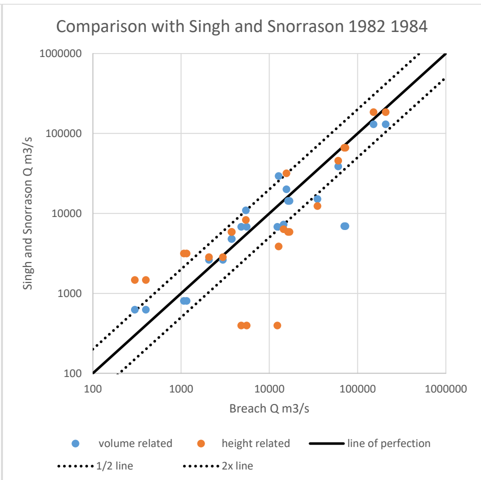
4.3. Dam Breach Discharge Estimated using Various Formulas

Comparison of dam breach discharges was also carried out by estimation using five (5) selective regression formulas developed namely by, Hagen, MLM, Singh and Snorrason, Costa, and Froehlich. These formulas were developed based on observed dam breach records. The independent variables were both water level elevation and storage capacity. The product of these two variables is termed as DF as previously explained. Only studies carried out by Singh and Snorrason adopted water level elevation and storage capacity separately in their calculation. Compared to others, Hagen's formula over-predicted the dam breach discharges as a majority of data were mostly scattered outside of the line of perfect agreement within a factor of two criteria. On the other hand, estimations using equations by MLM, Costa, and Froehlich were generally acceptable within factor of two order of magnitude. Singh and Snorrason's work differentiated itself from others using separate computation using separate formulas. The results were also generally falling in between the factor of two line. **Figure 4** shows the comparison of dam breach discharges of various formulas, Hagen, MLM. Singh and Snorrason, Costa, and Froehlich.

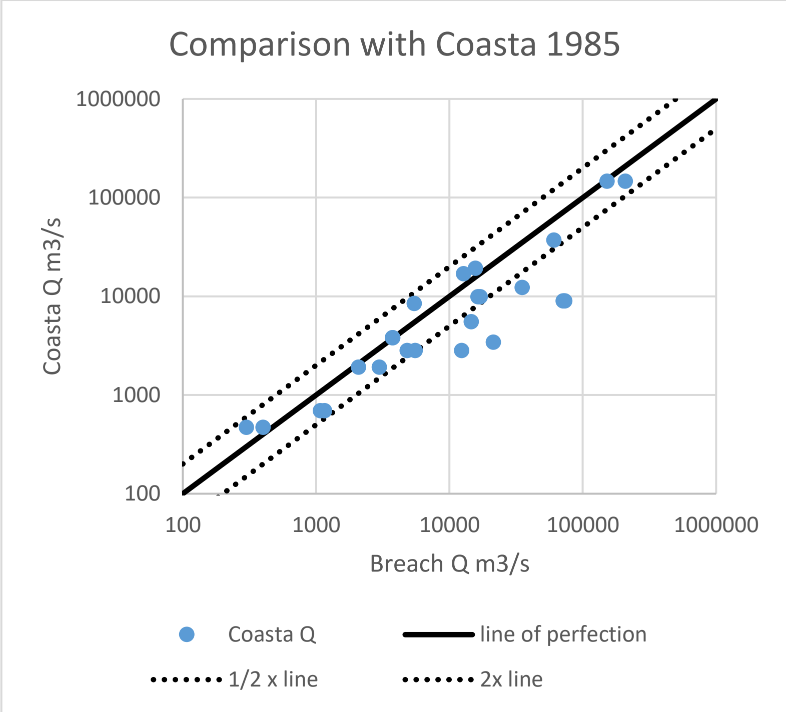


(a)

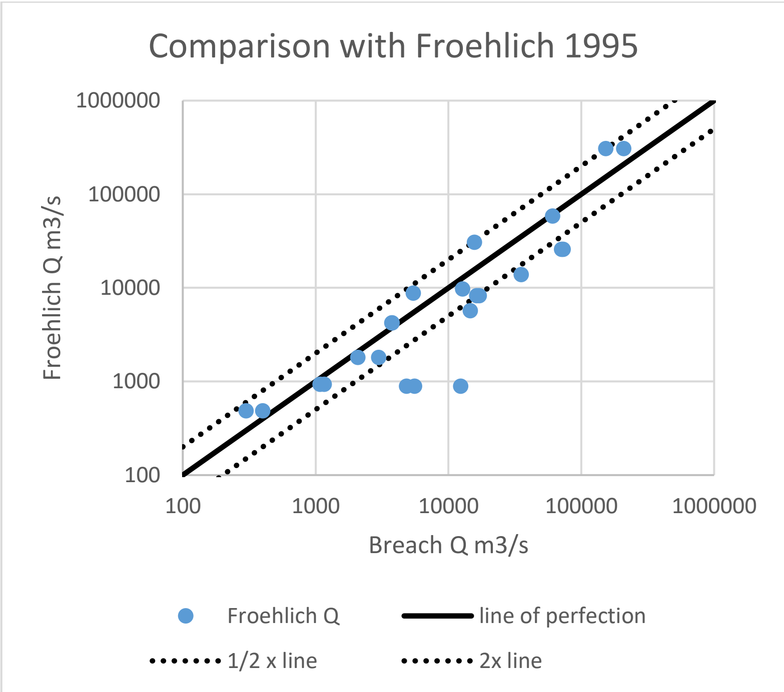




(b) (c)



(d)



(e)

Figure 4. Comparison with (a) Hagen, (b) MLM, (c) Singh and Snorrason, (d) Costa and (e) Froehlich (Black darkened line: 45° line of perfection, dotted lines (upper and lower): a factor of 2 line)

5. Conclusions

Dam break incident is an extreme rare event but the impact could be destructive with potential loss of human lives and property damages along the torrential flow path of a river basin. This study seeks to correlate the estimated dam breach discharges with PMP/PMF and other dam's physical parameters in Malaysia. The results and other associated parameters of fourteen (14) dam break studies were adopted for this analysis. Two (2) dam physical parameters, i.e. the height or elevation and the volume of storage behind the dam are directly affecting the magnitude of dam breach discharge. The product of these two parameters is termed as DF. These physically based parameters were also directly proportionate to the duration of the time of failure and the final breach width. A regression analysis was carried out to correlate the breach discharge and dam factor. A regression coefficient of 0.84 indicated a fair and consistent curve fitting of the regression formula. Comparisons of dam breach discharges were also made using various equations developed by Hagen, MLM, Singh and Snorrason, Costa, and Froehlich. The results were comparable at least to the same order of magnitude. The future endeavour is to undertake similar assessment and assignments on other existing dams in Malaysia. In this regard, there are fifty or so existing dams can be evaluated as well. From then on, the assignment can also be carried out based on other paradigmatic physically based dam erosion and breaching models but with much sophisticated input.

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Credit Author Statement

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Conflicts of Interest

The authors declare no conflict of interest.

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