Assessing Dam Breach Hazard in Cyprus

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SYNOPSIS. Accession to the European Union has driven dam safety reform in Cyprus. The Water Development Department (WDD) a sub-directorate of the Ministry of Agriculture, Natural Resources and Environment is responsible for ensuring Cyprus meets the requirements of the European "Directive 2007/60/EC on the Assessment and Management of Flood Risks". The directive requires member states to undertake flood risk assessments for all river basins and produce flood hazard risk maps and management plans where a significant risk is found to exist. The WDD is now in the process of developing Reservoir Flood Plans for its 56 International Commission on Large Dams (ICOLD) registered dams. The WDD engaged Mott Macdonald to provide advisory support and technical training in Hazard Ranking, Dam Break Hazard Analysis (DBHA), Flood Mapping and Emergency Planning.

Initial Hazard Ranking, based on dam height, reservoir capacity, downstream reach, and community characteristics, provided a, quick, semi-rigorous and rational basis for prioritizing WDD’s many reservoirs for future hazard analysis and planning. Current UK guidelines and methodology - modified to account for local conditions – were then applied to assess hazard posed by individual reservoirs and to develop contingency plans for those reservoirs. Rapid and Standard methodology outlined in the Draft Engineering Guide to Emergency Planning for UK Reservoirs (2007) (herein The Draft Guide) were used to assess flood risk for a number of dam breach scenarios, at each reservoir. Risk assessments based on the Interim Guide to Quantitative Risk Assessment for UK Reservoirs (Brown & Gosden, 2004)) was also undertaken.

A number of observations and conclusions were drawn from the work which may prove valuable for others preparing Reservoir Flood Plans and on-site Emergency Plans for Reservoirs in the UK and overseas.

ENSURING RESERVOIR SAFETY

BACKGROUND TO STUDY

Key Drivers

In an era inexorably linked to Climate Change, community perception of the risk posed to society by engineered structures such as large dams, is at an all time high. The Ulley Dam incident in late 2007 helped raise awareness in the UK whilst widespread damage and loss of life in New Orleans following Hurricane Katrina in 2005 – a result of failed flood levees- has been a catalyst for flood management policy review and dam safety reforms globally.

The European Floods Directive

The European Directive on the Assessment and Management of Flood Risks[1] (herein *The Floods Directive*) came into force on 26 November 2007 after EU environment ministers agreed there was a need for greater European co-ordination on flood risk management. The Floods Directive is designed to help Member States prevent and limit floods and their damaging effects on human health, the environment, cultural heritage, infrastructure and property. Whilst The Floods Directive does not specifically refer to flooding resulting from dam breaks it does require flood hazard maps to be produced for floods with a low probability, implying consideration of extreme event scenarios, such as dam break. The timetable for implementation of The Floods Directive is clearly set out. Member States have until 2009 to transpose the Directive into domestic law. In addition, Member States have to undertake preliminary flood risk assessments of their river basins and associated coastal zones by 2011, to identify areas where potential significant flood risk exists. By 2013, where real risks of flood damage exist, they must complete flood hazard and risk mapping for these areas. By 2015, flood risk management plans which document measures to reduce the probability of flooding and potential consequences must be developed for these zones. The management plans will address all phases of flood risk management but focus particularly on prevention, protection and preparedness.

UK Legislation

In the UK, Safety legislation for reservoirs was first introduced in 1930 after several reservoir disasters resulted in loss of life. This Act was superseded by the Reservoirs Act 1975, which today provides the legal framework to ensure the safety of large raised dams with reservoir capacities above ground level, greater than 25,000 cubic metres. The Water Act 2003, supplemented the Reservoirs Act and gave the Secretary of State powers to

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[1] EC Directive 2007/60/EC http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32007L0060:EN:NOT

direct reservoir undertakers (operators, users and owners) to prepare Reservoir Flood Plans, setting out the action they would take in order to control or mitigate the effects of flooding likely to result from any escape of water from the reservoir. The Department for Environment, Food and Rural Affairs (Defra) has funded the production of an *Engineering Guide to Emergency Planning for UK Reservoirs* to assist panel engineers and reservoir owners comply with the requirements of both Acts. The guide is currently available in draft form and will go out to formal consultation in Summer 2008. It will be published in 2009 when the Secretary of State will issue a direction to undertakers, making Reservoir Flood Plans a legal requirement. This extends the guidance on assessment of the likely consequences of dam failure developed in Brown & Gosden (2004).

In parallel with the aforementioned reforms, Defra is coordinating the transposition of The Floods Directive into UK law. Since August 2007, a UK Floods Directive liaison group involving both Defra and Environment Agency (EA) staff have been investigating options for capturing the requirements of The Floods Directive. The EA anticipate that many of the requirements will be covered by the existing Acts, with those outstanding to be potentially incorporated into the proposed 2009 Flood Bill.

A Water Scarce Island

Located 33° east of Greenwich and 35° north of the Equator Cyprus, the Mediterranean's third largest island, is water scarce. An arid climate of long, hot and dry summers and mild winters, gives rise to a mean annual precipitation (including snowfall) of just 460mm[2]. This equates to 2.670 million cubic metres (MCM) of rainfall over the total surface of the Government controlled southern region. The area's modest rainfall is irregular and unevenly distributed. Most of the precipitation falls in the Trodos Range (1,952 metres) in the centre of the island with minimum precipitation observed in the eastern plain and the coastal areas. Water scarcity is further compounded by Cyprus's abundant sunshine (11.5 hours per day on average in summer and 5.5 hours in winter) and winds, which together result in evapotranspiration of around 86%. This leaves just 370 Mm^3 of surface water available for development. None of Cyprus's 14 major rivers have perennial flow. In recent times, consecutive dry years and depleting groundwater reserves - a result of seawater intrusion into coastal aquifers - has lead to increased strains on water resources.

Since the neolithic period Cypriots have been drilling deep wells to combat water scarcity. Hardly surprisingly, today Cyprus's Water Policy is governed by the philosophy "not a drop of water to the sea". Cyprus's

[2] WDD Website http://www.cyprus.gov.cy

population of 900,000 rely heavily on groundwater and reservoir storage for reliable, year- round water supply. Following independence in 1960 a number of large projects were mounted to increase reservoir storage capacity, which today stands at about 330 million cubic metres. Providing this storage are 56 ICOLD registered[3] dams, ranking Cyprus as the most densely dammed country in Europe.

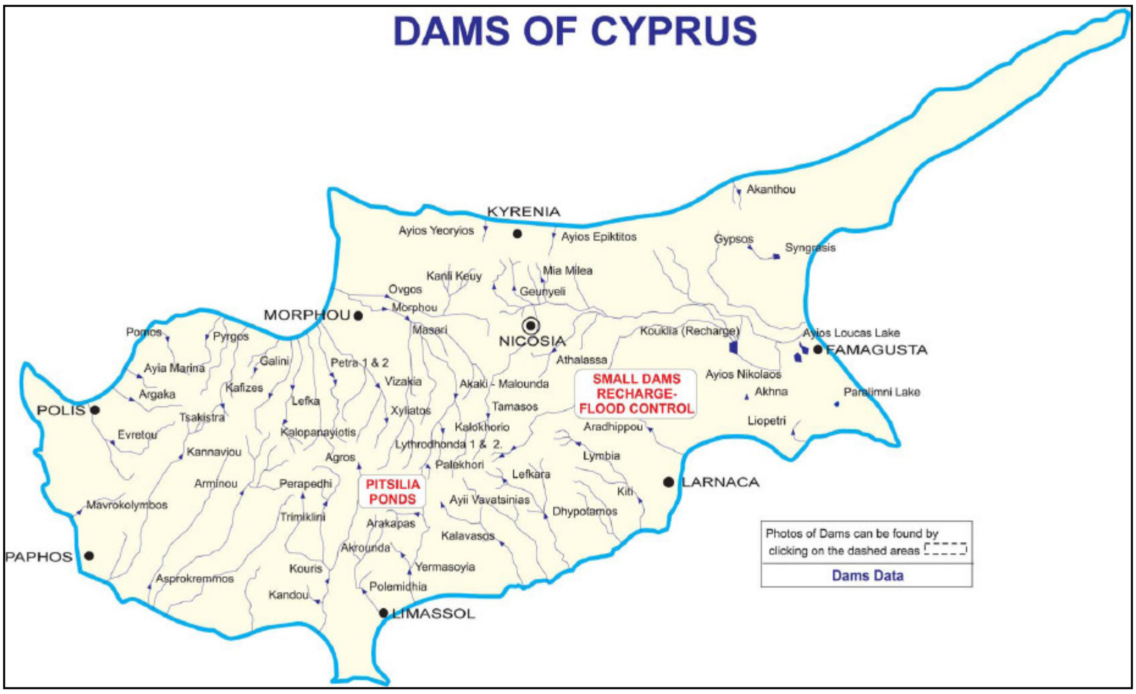

Fig 1. Location map of large dams in Cyprus *(Courtesy Water Development Department, Nicosia, Cyprus)*

Cyprus's major population centres such as Limassol and the capital Nicosia, lie in the floodplain downstream of large dams. Cyprus's 2004 accession to the EC means that it is now committed to the Flood's Directive. The WDD's traditional roles of implementing Cyprus's Water Policy and securing its water resources have been expanded to include implementation

[3] For inclusion on the ICOLD Register of Dams, a large dam is defined as any dam above 15 metres in height (measured from the lowest point of foundation to top of dam) or any dam between 10 and 15 metres in height which meets at least one of the following conditions: a) the crest length is not less than 500 metres ; b) the capacity of the reservoir formed by the dam is not less than one million cubic metres ; c) the maximum flood discharge dealt with by the dam is not less than 2 000 cubic metres per second ; d) the dam had specially difficult foundation problems ; e) the dam is of unusual design.
ICOLD : Technical Dictionary of Dams 1994

of the Floods Directive. Mott Macdonald was commissioned by WDD to provide advisory support and internal capacity building via technical training in Hazard Ranking, DBHA, flood mapping and emergency planning.

METHODOLOGY

Hazard Ranking

Faced with a large number of dams to analyze, WDD required a tool to focus investigations, identify priority dams and plan for future analyses. Hazard Ranking provided a quick, semi-rigorous and rational assessment of the Hazard potential of dams. In this paper 'Hazard' is defined as the consequence of a failure occurring whilst 'Risk' is the probability of that failure. Brown & Gosden (2004) recommends two approaches to Hazard Ranking. Cullen (1989) and Thompson (1994) both use a number of physical parameters such as dam height; reservoir capacity, the size and distance downstream of communities and floodplain topography to quantify the hazard associated with each dam. An analysis was carried out for all large dams under WDD's jurisdiction using both Thompson and Cullen. In practice, the application of both methods proved somewhat subjective (i.e. valley shape parameter can vary widely depending on the point of reference). Nonetheless, similar results were obtained from both methods, providing a rational basis on which to proceed. Furthermore, the results agreed in large with the expectations and confirmed the priorities set by experienced WDD Engineers.

Dam Break Hazard Analysis

DBHA provides information on the consequences of possible dam break scenarios for use in emergency action planning and risk analysis (downstream risks to population, property and environment). Depending on the level of risk involved, dam-break analyses may vary considerably in scale and detail. As a result, the *Draft Engineering Guide to Emergency Planning for UK Reservoirs* proposes two different approaches to DBHA: The Standard Method and the Rapid Method. The choice of method to apply to a particular situation should be based on sound engineering judgment and consideration of the complexity of the downstream floodplain and the population and infrastructure at risk.

In this study DBHA's were undertaken on four pilot reservoirs identified as having relatively high hazard potential during initial Hazard Ranking. Both Standard and Rapid Methodology were employed with mixed success.

Standard Method

The Draft Guide does not specifically define the process to be followed when undertaking a DBHA, but rather stipulates the scenarios to be analysed and the content of outputs. The Standard Method requires computational hydraulic modeling of the flood progression downstream of the dam to achieve the detailed outputs that are specified. Outputs required from each modeled scenario include: detailed (<1:10,000 scale) flood inundation maps; flood risk maps showing the extent of flooding and properties flooded where velocity is less than or greater than 2m/s; damage parameters of both velocity and depth at key points such as transportation infrastructure; flood hydrographs at specific internal (flood zone) boundaries; peak flow variation down the valley; and longitudinal sections down the valley showing thalweg and peak water levels.

The Standard Method was applied at two pilot dams for which Mott Macdonald provided technical advice during design and construction: Tamasos Dam, a 30m high earthfill dam sited on the Pediaios River, 23 kilometers upstream of the capital Nicosia (population 309,000); and the 38m high Akaki Malounda Dam on the Akaki River upstream of both Akaki and Malounda townships. Inundation maps and flood plans were produced for both these reservoirs. In urban Nicosia where the flood plain was both complex and extensive, a standard 1D modelling approach was found to be inadequate. Psuedo 2D modelling was undertaken as a stop-gap, but full 2D modelling is necessary to enable refinement of the flood mapping in future. Insufficient baseline data and constraints of the commission meant that it was inappropriate to undertake 2D modelling at this stage of the project.

Rapid Method

As its name suggests the Rapid Method is a quick and simplified approach to undertaking a DBHA. The Rapid Method can be applied to low consequence dams where the cost of undertaking the Standard Method is disproportionate to the increased accuracy and resolution of outputs achieved. It can also be applied as a screen to determine whether a Standard Analysis is required. The detailed outputs of the Standard Method are not required of the Rapid Method and the approach is thus less rigorous, less time consuming and requires less base data. Hydraulic parameters such as maximum average velocity and maximum depth are required only at certain cross section locations (flood zone boundaries).

The methodology employed in this study was based on excel spreadsheets developed by Brown & Gosden (2004). These were used to obtain breach outflow hydrographs for each scenario, route the flows downstream, and assess the hazard potential based on likely loss of life and damage. The Rapid Method was trialed for DBHA's at two pilot reservoirs: Yermasoyia; and Polemidhia.

Whilst the method requires relatively little input data and can be quickly undertaken (the requisite outputs and even crude flood outlines were developed in a day or two) the methodology can not be used to reliably predict flood outlines on wide or complex floodplains or where significant attenuation occurs in the flood plain or upstream of road embankments. This is because gross assumptions must be made regarding attenuation in upstream reaches. In such reaches, application of the Standard Method utilsing 1D or 2D hydraulic modeling has been recommended.

Software

Numerical modeling of a dam break is a computationally demanding routine due to the rapidly varying flow regime. The choice of numerical model and modeling platform for a Standard Method analysis is therefore an important aspect for consideration at project inception. Given the large number of reservoirs that WDD needed to analyse and the unavailability of reliable digital topographic datasets, a 1D hydraulic modeling platform was deemed the most economical and applicable solution. WDD sought an inexpensive and user friendly platform on which to develop their in-house modeling capability. At project inception, Mott Macdonald's in-house HYDRO-1D software and the United States Army Corp of Engineers HEC-RAS software were considered for the task. Research had previously shown that HEC-RAS might be unsuitable for dam break analysis given its inability to specify a computational time step less than 1 second.[4] In contrast, additional testing had shown HYDRO-1D to be robust under the same conditions.[5] HYDRO-1D has an additional advantage over HEC-RAS in that it can be seamlessly linked to a 2D model via HYDRO-2D in reaches where a 1D modeling approach might be unsuitable. To test model suitability both HYDRO-1D and HEC-RAS were used to model dam break in parallel for the first pilot reservoir. HYDRO-1D performed well and by using sound modeling techniques HEC-RAS also was able to successfully simulate the dam break. Given that HEC-RAS is free software the WDD opted to continue to use HEC-RAS for future analyses.

Treatment of transportation embankments

By virtue of their ability to impound large volumes of water, the behavior of transport embankments within the flood plain can drastically affect flood impacts. The net effect can be both positive and negative. They can increase inundation upstream whilst lessening downstream impacts by attenuating peak flows. Alternatively if the embankment breaches early in

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[4] Crowder, R.A., et al., (2004), Benchmarking and Scoping of 1D Hydraulic River Models, Environment Agency Research Technical Report W5-105/TR2L – Test L (Contraction & Expansion), pg 15

[5] Wardlaw, R (2006) Benchmarking the HYDRO-1D Hydraulic River Modeling Package, The University of Edinburgh, pg 109

the dam break flood, then this may add to the overall peak and compound existing flooding. A subjective analysis must be made of the treatment of each in turn. Consideration must also be given to the extent of blockage of culverts or openings in the embankment by debris. Advice is provided in the Draft Guide.

Derivation of Breach Outflows
The Draft Guide specifies Standard Scenarios to be analysed such that Reservoir Flood Plan users can comprehend the wide range of possible scenarios and the severity and assumptions in the "standard scenario" and so there are repeatable, conservative estimates of the extent and impact of dam failure. The Standard Analysis Scenario outlined in The Draft Guidelines proposes the following two scenarios as a minimum:

Rainy day "dam failure" – 10 000yr inflow to reservoir causing dam failure. Provides a likely maximum dam break flood from a full reservoir;
Rainy day "No dam failure" – 10 000yr inflow to reservoir. Required as a baseline for determining the incremental loss of life and damage in the event of dam failure.

In addition a third "optional" scenario, was analysed in this study:

Sunny day "dam failure" – No reservoir inflow, reservoir water level at spillway crest. This can be useful for emergency planning where the peak dam breach flow is significantly less than the rainy day "dam failure" scenario.
The Draft Guide recommends estimating peak breach discharges using methodology outlined in Brown & Gosden (2004). For embankment dams the peak discharge equation is proposed by Froehlich (1995):

$$Q_P=0.607\ V^{0.295}H^{1.24}$$

where: Q_p = Peak breach discharge (m^3/s);
V = Reservoir capacity (m3);
H = Height of peak reservoir level above dam base (m);

Brown & Gosden (2004) use methodology outlined in CIRIA Report C542 (2000) to derive a simplified triangular breach hydrograph with total volume equal to the reservoir volume, subject to reducing the Time to Peak (Tp) (initially taken as 120 times dam height) and Time of Event (Te) to ensure that the hydrograph volume remains the same as the reservoir volume.

It should be noted that modern predictive breach models offer a much more dam specific approach to developing breach discharge hydrographs since they consider the physical development of the breach through the core of the dam. Given that these models are still in early stages of development and the number of reservoirs to be analysed by the WDD, these models were not considered for this study. Future studies should consider the use of these models.

Consequence Assessment

The final part of the DBHA is the consequence assessment. This is intended to identify areas likely to be inundated allowing those responsible for emergency planning and response to make informed decisions when planning for possible future events, and when dealing with actual events. It also provides data which can be used by others in assessing the risk to infrastructure.

Again, the Draft Guide recommends methodology specified in Brown & Gosden (2004). The methodology is used to broadly estimate the:

a) Number of buildings in the inundation area, and the area and type;
of non-residential property, and the degree of damage;
b) Number of people (population) at risk;
c) Likely Loss of Life (the base case is with no warning);
d) Third party property damage.

The Consequence class of the dam is a function of the Likely Loss of Life and Third Party direct flood damage.

Whilst the data required for such an analysis is generally readily available in the UK, it is anticipated that in many overseas situations this data may not be available or may require considerable effort to source. In this study, base line data such as average house prices and average number of inhabitants had to be estimated adding further uncertainty to the analysis.

PROBABILITY OF FAILURE ASSESSMENT

Probability of failure assessment is carried out in order to determine the risk of failure of a dam. Methodology provided in Brown & Gosden (2004) was again used as the basis for the assessment. Standard spreadsheets that estimates the risk (or probability) of dam failure were modified to account for Cypriot conditions. For instance, one would expect the risk of failure from a seismic event to be considerably greater in Cyprus than in the UK and hence the changes were made to reflect this. Similarly many of Cyprus's dams remain dry year round, filling only with the infrequent rainfall. Such dams are susceptible to maintenance issues not normally encountered in the UK.

CONCLUSIONS

A number of observations and conclusions were drawn from this work which may prove valuable to others undertaking similar work in the UK and overseas:

-Hazard Ranking is a quick, semi-rigorous and rational tool for undertaking an initial assessment of the relative hazard posed by dams and where there are a number of dams to consider can assist in the prioritization of emergency planning efforts.

-DBHA's should focus strongly on the requirements of the end user. There is an overriding need for a consistent approach to undertaking DBHA and reporting results;

-In undertaking DBHA's it is important not to lose sight of the uncertainty inherent in both dam breach modeling and flood mapping. The approach should always err on the side of caution but the resources attributed to a particular component should reflect the uncertainty and in turn the flood impact associated with the uncertainty. i.e. there may be little point analyzing in detail debris blockage at a transportation embankment if there is uncertainty regarding the Time to Peak of the breach which generally has a considerable impact on the peak breach outflow. However, it is important to consider the hazard envelope i.e. the overall flood outline from all scenarios considered;

-Assumptions regarding DBHA's should be clearly identified on published outputs. Modern flood mapping and Geographic Information Systems (GIS) techniques produce detailed outputs which don't necessarily reflect the quality of the underlying data or uncertainties in the methodology or model used. They can therefore be easily misrepresented. Assumptions made in developing the flood models (there are lots of them) are not readily apparent from viewing a flood map and these can influence the results considerably;

-Generally speaking, current UK DBHA and Reservoir Emergency Planning guidance can be successfully adopted for use overseas provided local idiosyncrasies and differences are recognized and the methodology is modified accordingly. Overseas dams can be subject to different failure mechanisms and have different failure probabilities to their UK counterparts. Care is needed with emergency planning as both the scale and nature of the hazard and the emergency response can be vary considerably;

-The application of UK guidance overseas can be difficult where certain base data (e.g topographic survey, socioeconomic, utility and services, dam monitoring records, etc) are not available, or not to the standards typically encountered in the UK.

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