An-Najah Univ. J. Res., Vol. 12, (1998) 40-54

Flood Routing Techniques for Incremental Damage Assessment

طرق متابعة الفيضانات لاستخدامها في حساب الأضرار التفاضلية

Anan Jayyousi

عنان الجيوسي

Department of Civil Engineering, An-Najah N. University, Nablus, Palestine.

Received: (30/3/1996), Accepted: (25/11/1998)

Abstract

Incremental damage assessment (IDA) for dam safety evaluation determines whether or not a significant increase in flooding will result from dam failure. Since IDA depends on a prediction of downstream flooding with and without dam failure, it is essential that flood routing be performed using an appropriately selected and properly applied technique. Conclusions drawn from an IDA can be distorted if flood routing is inappropriately applied or if unrealistic breach parameters are used.

In this paper, the results of a study which assesses the accuracy of alternative flood routing technique for use in IDA are reported. Flood routing techniques that are evaluated cover dynamic routing, kinematic, Muskingum-Cunge, and normal depth storage routing. These techniques were evaluated against the more accurate two-dimensional flood routing technique contained in the diffusion hydrodynami c model (DHM). The assessment was conducted for conditions which typify those that exist in Palestine. The goal of the study is to develop guidelines for selection of flood routing techniques for use in IDA and for interpreting IDA results in different settings. The overall outcome shows that the performance of one dimensional techniques in predicting peak stages

performed very well when using a full one dimensional model especially in cases where there is a uniformity in the water course.

إن الهدف الرئيسي من حسابات الأضرار التفاضلية هو معرفة ما إذا كانت الزيادة في الفيضان الناتج عن انهيار السد أو أي منشأ مائي ذات أهمية أولاً.

لحساب هذه الأضرار التفاضلية يجب معرفة كمية التدفق أسفل السد في حالة انهيار السد أو بقائه، ولهذا فانه من الضروري اختيار الطريقة الأفضل والتطبيق الأمثل لهذه الطريقة حتى نستطيع الحصول على معلومات صحيحة لحساب الأضرار التفاضلية. إن المعلومات المضطربة والغير صحيحة نتيجة استخدام طريقة غير ملائمة أو أي استخدام خاطئ لهذه الطريقة سيؤدي إلى نتائج خاطئة لحساب الأضرار التفاضلية.

يستعرض هذا البحث نتائج الدراسة على دقة الطرق المختلفة في حساب كميات التدفق وتمرير الفيضانات. إن الطرق التي تم تغطيتها في هذا البحث تشمل الطريقة الديناميكية، طريقة مسكنجم-كنج وطريقة المخزون والعمق العادي.

تم تقييم ومقارنة نتائج هذه الطرق المختلفة مع النتائج التي تم الحصول عليها من الطريقة الأكثر دقة والتي تأخذ بعين الاعتبار التسارع في الاتجاهين الموازي مع محور المجرى المائي والعمودي عليه. لقد تم فحص الطرق المختلفة ومقارنتها لأنواع مختلفة من المجاري المائية التي تشابه بطبيعتها المجاري المائية الموجودة في فلسطين بهدف وضع الأسس والمقاييس التي تتحكم بتحديد الاختيار الأمثل الذي يجب استخدامه حسب طبيعة المجرى المائي والظروف الأخرى عند حساب الأضرار التفاضلية

Introduction

Accurate flood routing procedures are needed for various aspects of dam safety assessment, including incremental damage assessment (IDA). Several one-dimensional flood routing techniques, which are contained in computer models such as HEC 1 [1] and DAMBRK [2], are commonly used by the engineers who are responsible for dam safety studies. Each technique is based on a different set of underlying assumptions and has its own limitations. In this paper we present some preliminary results of an evaluation on the performance of these techniques for estimating 1) peak flood stages under natural and dam break flood conditions; and 2) incremental flooding depths for use in IDA.

Our evaluation covers dynamic routing as contained in DAMBRK and kinematic, Muskingum-Cunge, and normal depth storage and outflow routing as contained in HEC 1. The evaluation was performed for several hypothetical channel configurations and flood events. Also, the evaluation was performed for routing actual dam failures of the Teton Dam, Buffalo Falls dam, Toccoa Falls dam, and Quail Creek Dike.

This paper is divided into presentations of incremental damage assessment concept, flood routing techniques used in our study, our evaluation methodology, results and conclusions.

Incremental Damage Assessment

Incremental damage assessment (IDA) has become a commonly applied procedure in the evaluation of the safety of existing dams. IDA is recognized by many state dam safety regulators, the Federal Energy Regulatory Commission (FERC), the U.S. Bureau of reclamation, and the U.S. Army Corps of Engineers. IDA is used to determine whether or not a significant increase in downstream flood damages would result due to dam failure during a flooding event. If incremental damages are significant above some flowrate,. that flowrate is defined as the base safety condition (sometimes referred to as the critical flood), below which the dam should be designed not to fail. If the critical flood is less than the inflow design flood, IDA may be used to justify rehabilitation measures that will be required so that an existing dam will pass the critical flood without failure. Alternatively, an existing dam may already be capable of passing the critical flood without failure, and investment in rehabilitation measures is not justified. Thus investment in rehabilitation measures is not justified even though the dam would fail at a flow rate less than the inflow design flood.

Downstream damages may be expressed in various ways, such as depth of flooding, flow velocity, economic damages, or threat-to-life. To assess these damages requires dam break analysis and flood routing. Flood routing is performed for a range of reservoir inflow floods, varying in magnitude up to the inflow design flood, under the assumptions of dam failure and no dam failure. If appropriate more than one dam failure mode is considered. Accuracy in predicting both the absolute extent and depth of flooding, and the extent and magnitude of incremental flooding due to a sudden release of the reservoir contents are important.

"Significant" downstream damages can be defined in various ways. Most commonly incremental stages exceeding one-foot or two-feet are considered to be significant, where incremental stage is defined as the difference between peak no-failure and peak failure stage. Peak no-failure stage is also important because it determines the extent of flooding, and therefore which facilities will be affected by incremental flooding. Some regulators consider the product of average flood velocity and depth of flooding in the area of incremental flooding. In other cases, incremental property damage or threat-to-life are specifically evaluated. Sometimes the probability of occurrence of incremental flooding is also taken into account in a risk assessment of existing dam safety or rehabilitation alternatives. In all cases, flood routing accuracy is crucial to obtaining meaningful results for IDA.

Flood Routing Techniques

Flood routing is a three-dimensional, unsteady process in nature. In engineering practice, flood routing calculations are commonly simplified by using one-dimensional techniques in which variations in the transverse directions are averaged. Also the effects of debris and sediment are usually ignored, and channel boundaries are assumed to be rigid. In this section, we summarize the four one-dimensional flood routing techniques which we have evaluated, and the two-dimensional flood routing technique (DHM) against which we have compared the one-dimensional techniques. The basis for making this comparison is described in the "Evaluation Methodology" section.

Two-Dimensional Flood Routing

Flood flows with significant transverse components, (e.g., in flood plains) may be more realistically modeled with equations that describe the motion of water in two dimensions, rather than only one dimension. According to Williams (1993), the main assumptions made in the DHM [3] two-dimensional, unsteady flow model are: 1) vertical accelerations are ignored through vertical averaging; 2) flow is fully turbulent; 3) vertical pressure distribution is hydrostatic; 4) flow boundary is rigid; and 5) water is incompressible and homogeneous.

One-Dimensional Dynamic Flood Routing

This technique involves simultaneously solving the momentum and continuity differential equations. Williams [4] described the following assumptions made in additions to those described for the two-dimensional case: 1) the x-dimension is along the centerline of the river; 2) effects of transverse velocity distributions are approximated through lateral subdivision of the channel; and 3) bed slope is less than 1:10. These differential equations for momentum and continuity for one-dimensional models can be solved by: the method of characteristics, the explicit finite difference, implicit finite difference, or finite element methods. We implemented the DAMBRK model which uses the four-point implicit finite difference technique.

Kinematic Routing

We evaluated the kinematic routing technique contained in HEC 1. Kinematic routing refers to methods which use the continuity equation and a steady -uniform simplified form of the momentum equation. It is based on the one-dimensional flow equations, neglecting the convective acceleration terms. Since these methods do not fully consider accelerations, they are termed kinematic rather than dynamic. For a kinematic wave technique to be applicable, Ponce [5] state that the value of (S L)/(Y Fr) should be greater than 20, where S is the bottom slope; L is the reach length; Y is the normal depth; and Fr is the Froude number at normal depth. Thus this routing technique cannot be expected to work well for flood routing in river and flood plains with low slopes.

Muskingum-Cunge Routing

The Muskingum-Cunge routing option from HEC 1 was used in this study. Muskingum-Cunge is a modified version of the Muskingum method, developed by [6], in which the local convective acceleration terms in the one-dimensional flow equation are neglected. Cunge assumed a single-valued, depth-discharge relationship and applied a four-point finite difference technique to derive expressions for the Muskingum routing coefficients X and K.

Normal Depth Storage and Out flow Routing

We used the normal depth storage and outflow routing (sometimes called level pool method or reservoir routing) option in the HEC 1 model in our work. Storage method are based on a relationship between storage and discharge combined with the conservation of mass equation:

I-O = δS/ δt where I and O are the average inflow and outflow, respectively, during the time period δt; and δS is the associated change in storage.

Table 1. Peak Stage Error (Cross section 6, 50% PMF)

Case	Slope	DAMBRK	Muskingum-Cunge	Kinematic	Storage
Widening-Failure	0.002	0.55	0.61	3.10	1.00
	0.010	0.35	-0.15	-0.20	-1.10
	0.030	0.21	-0.90	-0.80	-0.90
Widening Non-Failure	0.002	0.21	0.25	0.60	0.40
	0.010	0.16	-0.15	-0.15	-0.25
	0.030	0.12	-0.10	-0.10	0.25
Narrowing Failure	0.002	0.20	-0.70	3.50	-1.40
	0.010	0.90	-0.30	-0.50	-0.70
	0.030	-0.35	-0.90	-0.90	-1.10
Narrowing Non-Failure	0.002	-0.20	-0.51	-0.50	-0.60
	0.010	-0.10	-0.20	0.10	-0.45
	0.030	-0.05	-0.15	-0.15	-0.22

Table 2. Incremental Stages (Cross section 6, 50% PMF)

Case	Slope	DHM	DAMBRK	Muskingum-Cunge	Kinematic	Storage
Widening	0.002	4.37	3.90	3.90	6.56	3.96
	0.010	4.89	4.57	4.57	4.69	3.90
	0.030	4.73	3.72	3.72	3.87	3.44
Narrowing	0.002	3.24	3.38	3.38	6.49	3.17
	0.010	5.16	4.56	4.56	4.67	3.95
	0.030	4.21	3.81	3.81	3.79	3.64

Evaluation Methodology

Data on extreme floods, especially dam break floods, are available for only a few events covering a limited range of flow magnitudes and channel conditions. Therefore, in this paper we have chosen to focus on hypothetical dam-river systems and flood events, for which we can systematically vary factors such as slope, roughness (Manning's coefficient), cross sectional geometry, flood characteristics, and dam breach parameters. We choose a range of channel factors, which are representative of the range of conditions that exist in Palestine. We considered subcritical (mild slope of 0.002), supercritical (steep slope of 0.03), and near-critical slope (slope of 0.01) flow regimes in widening and narrowing reaches, with trapezoidal cross sections. The gentle slopes can be found in the coastal areas and in the Jordan Valley in Palestine while the steep slopes can be found in the hilly areas of the West Bank. The value of manning coefficient that has been considered here is 0.05.

A natural reservoir inflow flood hydrograph with a "probable maximum flood" (PMF) peak of 250,000 cubic feet per second (cfs), a seven-hour flood volume of 72,000 acre-feet, and a triangular form was used for non-failure cases. The PMF is the possible maximum flood that will result from a certain catchment area under the most hydrologic, meteorologic, and hydraulic conditions. Evaluation were performed for several inflow hydrographs which were derived by multiplying the PMF hydrograph ordinates by a percentage, varying from 10% to 100%, in 10% increments. Dam break flood hydrographs were generated using the breach hydrograph capabilities of the DAMBRK model for: 10-100% PMF inflow hydrographs; a 150 foot high dam; a 13,025 acre feet reservoir capacity at 0.5 feet of overtopping, at which the dam was assumed to fail; a breach width of 50 feet; and a time to failure of 0.2 or 0.8 hours. Failure and no-failure floods were routed through a reach below the hypothetical dam with 11 cross-sections between reaches, spaced 5,000 feet a apart.

We adopted the DHM two-dimensional unsteady flow model to provide estimates of 'true' flow conditions for the hypothetical results. Performance of the one-dimensional techniques was compared against DHM predictions. Our choice of the DHM model was based on an evaluation, which was performed for observed floods resulting from the Teton and Buffalo Creek Dam failures in the united States of America. Data for these events, including the DAMBRK input files, were provided by Dr. Danny L. Fread [7]. Our evaluation shows that, for both dam failure floods, DHM predicted peak flood stages to within one foot of observed stages whereas DAMBRK diverge from observed peak stages by up to eight feet, and other one-dimensional techniques by up to twenty feet for the same dam break flood simulations [8]. In all cases, DHM slightly overestimated stages. Therefore, by comparing the performance of one-dimensional techniques with DHM, we have probably introduced a slight bias into our estimated errors specifically, overestimates in the performance of one-dimensional methods can be expected to be slightly lower than their true magnitudes, whereas underestimates are probably slightly higher that their true values.

Discussion of Results

Errors in stage and incremental stage predictions for the one-dimensional techniques were calculated for all hypothetical reservoir inflow hydrographs for both dam failures and no-failure cases in widening and narrowing channels. An example of the estimated errors in predicted peak stages is presented in Figure 1, for the case of widening channel with a slope of 0.01. The figure shows, for each of the one-dimensional techniques, the errors for a no-failure case, and two failure cases (0.8 and 0.2 hours to failure) as a function of peak inflow rate. The figure shows that the higher the peak inflow, the bigger the error in estimating the stage. The figure also shows the accuracy of the different models under the failure and no-failure conditions. Figure 2 shows estimated incremental stages at cross section 10, 45,000 feet downstream from the dam as a function of percent PMF, for each one-dimensional technique and DHM. From Figure 2 one can develop an idea about the performance of the different models in predicting the incremental stages.

Table 1 shows peak stage errors at cross section 6, located half-way through the hypothetical reach, for the 50% PMF flowrate. The table shows the errors resulted from using the different techniques as a function of the flow conditions whether it is subcritical, critical, or supercritical. Table 2 contains incremental stages at cross section 6, for the 50% PMF flowrate, for each one-dimensional technique and DHM. The value of 3.96 for example is the incremental stage predicted by the storage routing technique. This value is lower than the 4.37 predicted by the more accurate DHM model. The differences between the incremental stages predicted under the DHM model and the one-dimensional techniques will be considered as the errors from that one-dimensional technique.

In the widening case, errors in predicted peak failure stages were consistently higher than for no-failure flood peaks associated with the same magnitude (percentage) inflow event. Also, there was a trend for errors in predicted peak stages to increase with increasing flowrates for both failure and no-failure cases. Generally, these errors decrease with distance downstream from the dam, although the rate of decrease is greater for failure cases were hydrograph attenuation is greater than for no-failure. Some results listed in Table 1 do not follow the general trend especially in the case were the slope of the channel is 0.01. In this case, the flow conditions were around the critical conditions which causes some variations in the results.

Unlike the widening case, peak stage errors generally increase with distance downstream from the dam in the narrowing case. Although these errors tend to change less as a function of flow rate, than in the widening case, some trends can be detected. For mild slopes (subcritical flow regimes) the errors tended to be negative at low flows and positive at high flows. For steep slopes, errors were negative and increased as peak inflow rate increased especially for

DAMBRK. Again, with the widening case, errors is in predicted peak failure stages were consistently higher than for no-failure flood peaks associated with the same magnitude (percentage) inflow event. A summary of our results for stages and incremental stages for each of the one-dimensional techniques are presented in the following subsection.

Dambrk

Peak stage: DAMBRK most frequently yielded the most accurate absolute stage predictions for sub and supercritical flows. However, for nearcritical conditions, DAMBRK was more likely to experience convergence problems. It performed worse than both of Muskingum-Cunge and kinematic method. For cases of low slope, the kinematic method performs very poorly. The storage method gave the largest peak stage prediction errors. DAMBRK consistently overestimated peak stages because it ignores lateral velocity. This reduce the predicted velocity, and hence increase the predicted stage. All one-dimensional techniques ignore lateral velocity, but the effect of this was offset, or amplified, by other limitations associated with the non-dynamic nature of the other techniques. These limitations include the limitations on using these techniques for unsteady flow conditions, two or three-dimensional modeling, and the limitation on using these non-dynamic techniques fort non-uniform flow regimes.

Incremental stage: In our preliminary evaluations, DAMBRK generally overestimated incremental stage for both the widening and narrowing channels. Errors in incremental stages decrease, or only slightly increase, with increase in the peak inflow rate. For the narrowing channel, It was founded that higher errors in incremental stages at subcritical and near-critical flow conditions. For the case shown in Figure 2, DAMBRK would imply a critical flow (base safety conditions) at 60 % PMF based on a two-feet criterion for significant incremental stage, whereas the more accurate DHM showed the critical flow to be at 51% PMF.

Muskingum-Cunge

Peak stage: For widening and narrowing cases, underestimation of peak stages usually resulted for supercritical flows because the dynamic slope term (in the connective acceleration term of the momentum equation) was underestimated (due to simplification of this term). For subcritical flows, when the dynamic slope term was overestimated, overestimation of the peak stages usually resulted.

Incremental Stage: Incremental stages were generally underestimated for both widening and narrowing channels. Errors appeared to generally increase with increasing peak inflow rate. For the case shown in Figure 2, Muskingum-Cunge would imply a critical flow (base safety conditions) at 44 % PMF based on a two-feet criterion for significant incremental stage, whereas the more accurate DHM showed the critical flow to be at 51% PMF.

Kinematic Routing

Peak stage: Since kinematic routing ignores convective acceleration, it always overestimated peak stages for subcritical flows, and usually underestimated for supercritical flows.

Incremental stage: Kinematic routing underestimates incremental stages for all cases except the subcritical flows where it grossly overestimates, since the applicability criterion [5] is not met. The effect is illustrated in Figure 2, where the two-feet direction for significant incremental stage is never met, even at 100% PMF, while the more accurate DHM showed the critical flow to be at 51% PMF. Thus kinematic routing cannot be recommended for use in estimating incremental stage for subcritical flow conditions.

Normal Depth Storage Outflow Routing

Peak Stage: The normal depth storage and outflow technique assumes uniform steady flow, and thus ignores the entire momentum equation. As a result, the technique generally overestimated peak stages at higher flows, and underestimated them at lower flows. Thus overestimation also characterize the predicted peak stages for the very high flows associated with failure cases in reaches closes to the dam (e.g., within two miles). Peak stages attenuated two rapidly in the failure case for both super- and sub- critical flows since inertial effects were not properly considered. The normal depth storage and outflow technique assumed uniform steady flow and thus generally underestimated peak stages for the narrowing case, unlike the widening case in which it generally overestimated.

Incremental stage: For widening and narrowing cases, Storage routing significantly underestimated incremental stages. These errors generally decrease with increasing peak inflow rate, but increase in the downstream direction. For the case shown in Figure 2, the normal depth storage and outflow technique would imply a critical flow (base safety conditions) at 42 % PMF based on a two-feet criterion for significant incremental stage, whereas the more accurate DHM showed the critical flow to be at 51% PMF. Incremental stage errors were so large that we don't recommend storage routing for use in IDA.

Conclusions

Overall, the performance of one-dimensional techniques in predicting peak stages showed that DAMBRK performed very well, and normal depth storage and outflow did worst. This overall ranking matches the degree of simplification in representing the true flood routing situation. However, in some circumstances DAMBRK performed worst, and Normal depth storage and outflow was superior to the Muskingum-Cunge or kinematic techniques. Thus, it is important to understand the specific performance characteristics of all the methods when selecting one for a flood routing application.

In assessing a two-feet incremental stage criterion, DAMBRK performed best for the widening channel. However, Muskingum-Cunge generally performed better at predicting incremental stage in the narrowing case. Significant errors in predicting incremental stages were found for most cases in which storage routing was evaluated, and therefore we do not recommend its use for this purpose. Similarly, we do not recommend kinematic routing for subcritical flow conditions in which the applicability criterion [5] is not met.

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