Risk assessment of a dam-break using GIS technology

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Abstract Flood disasters cause massive loss of human lives and immense damage to the infrastructure and economic activities, not only in Turkey but also all over the world. Governments consider several long-term and short-term precautions for flood control. The numerical simulation of dam-break problems could be accomplished with geographic information systems and innovation maps. Spread of the flood wave after a dam break can be predicted using these enabling technologies. This kind of advanced modelling technology is becoming an inevitable tool for the decision-making process. Data produced by GIS are used as initial values for FLDWAV. ArcView GIS has been used to produce a Digital Elevation Model and visualization of dam-break effects and propagation of a possible flood wave. Using GIS techniques and hydrologic modelling software, possible effects and damage of a dam-break flood have been investigated and results were simulated to show significant dam break effects on the region.

Keywords Dam break; flood; GIS; risk assessment

Introduction

Istanbul, which is located on two continents, is the largest city of Turkey with a population of over 12 million. It is a combination of a very rich historical background and a modern appearance (Seker *et al*., 2001). Water demand of Istanbul is supplied from 7 lakes and reservoirs, which are in service. In this study one of these reservoirs, Alibeykoy Dam, has been selected for the case study. In rapidly developing cities such as Istanbul, settlement areas extend enormously at an unexpected rate. This out-of-control situation causes new problems. As the planned structures take a long time to build, or the regulations are not applied and political decisions interfere, settlement areas are mostly developed within the dam areas.

In such cases, the risks caused by breakage of the dams, which have been constructed for a number of purposes such as provision of drinking and irrigation water as well as generation of electric power, could reach serious proportions. Most of the dams constructed so far are earth-fill dams. The breaking mechanism of such structures could be one or more of numerous reasons like intake flow at unforeseen level, inadequate foundation works, different settling, landslides, earthquakes or improper project design. Past experiences show that the time between the occurrence of a breach and discharge of the dam reservoir ranges from 15 minutes to 5 hours. Therefore, it is necessary to make again the risk assessment and accordingly the plans of rescue and evacuations for the dams which remain within the settlement units during their economic lifetime.

On the other hand, it is estimated that the overflow characteristics change due to global climate change. This development, which is beyond control, poses itself to be another reason for risk assessment of the existing dams. Terrorism is regrettably another fact of the 21st century. While mankind considers measures against such inhumane activities, especially after the events on September 11th 2001, dams, too, have to be borne in mind within the sphere of such extensive measures. Concrete dams, which usually are less susceptible to collapse compared to the earth-fill dams, must also be dealt with in this assessment.

In risk assessment of a dam surrounded by settlement units, the main objective is the use

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of contemporary techniques producing and using reliable data together with classical methods. To be more precise, compilation in digital media of the topographic, demographic and socio-economic data of the area downstream, and production of data to be used in geographical information systems and classical methods, as well as evaluation of the results thus obtained again in GIS in order to produce risk maps must be considered as one of the contemporary methods.

In order to provide this kind of risk map and an early warning system, we need to find the time and water elevation of cross sections during the dam failures, obtaining main data and the damage of the dam breach flood. In this study solution techniques for dam breach formation that cause failure of the dam and the routing of flood waves were investigated.

Study area

The selected project area of this study is Alibeyköy Dam, which is a typical example of the situation mentioned in the previous section. When the construction of the dam started in 1966, the area was completely a rural area. In 1983, after the construction was completed, human settlement started in this area. Today, settling density of the area is higher than before. Floods created by the Alibeyköy Dam failure may cause large amounts of property damage and large losses of human life.

In the failure scenarios of Alibeyköy Dam, different probabilities were taken into consideration. In this study the overtopping failure examined with the worst-case scenario, which is the flood and closed spillway gates while the reservoir water elevation is equal to the crest of the dam elevation.

Construction of Alibeyköy Dam on the Alibey Stream in Istanbul started in 1966 and in 1968 it started to retain water temporarily. It was taken into full service in 1983. For the purpose of this application, apart from the data given in the Table 1, the 1,000-year flood hydrograph, area-elevation curve of the dam reservoir and the spillway discharge curve have been obtained from DSI (State Waterworks of Turkey) and used in this study.

Methodology

In this study the "Breach" model for breach formation, and the Fldwav model for flood routing were used with the computer programs having the same names (Fread, 1978; Bellos and Sakas, 1987). The necessary cross-sectional data were obtained from a numerical area model of ArcView GIS by using the digital maps of Istanbul Municipality. At the end of the study the time of the flood reaching the cross sections, and the peak values of water elevations at these cross sections, were calculated and the time of maximum water elevation at the last cross section flood wave reaching to the furthest cross section from the dam of the worst scenario was estimated. It is seen that the arrival time of maximum water elevation value at the last cross section allows enough time to evacuate the settlement areas.

Numerical model of dam breach

Formations of a breach in earth-filled dams occur gradually in the course of time. When examples of many destroyed dams are examined, it is seen that the breach reached as far as the foundation of the dam body by means of attrition after the first occurrence of the breach. In the meantime, examination of some other failed dams revealed that formation of the breach stopped also somewhere in the middle of the dam body. Dimensions of the breach are defined in terms of width and the depth of the breach. Dimensions of the breach and the speed of its formation are the factors determining the shape and size of the overflow hydrograph coming out of the breach. Therefore, it is very important that the engineers and hydrologists determine the dimensions and formation speed of the breach so that the overflow hydrograph coming out of the breach can be accurately ascertained.

Table 1 Data about Alibeyköy Dam

General data Characteristics	
Drainage area	160 km^2
Annual mean precipitation	800 mm/year
Annual mean flow	280 mm/year
Predicted flow	160 km^2 × 280 mm/year
Reservoir	
Maximum water level	32.00 m
Maximum capacity	65 × 10^6 m^3
Maximum reservoir area	4.76 × 10^6 m^2
Maximum operation level	26 m
Minimum operation level	10.50
Minimum operation area	0.426 × 10^6 m^2
Dead volume	0.476 × 10^6 m^3
Active volume	35 × 10^6 m^3
Flood peak	1,000 m^3/sn
Downstream river capacity	80 m^3/sn
Body	
Type	Earth-fill
Volume	2.00 × 10^6 m^3
Crest level	34.00 m
Crest weight	15.00 m
Crest length	6.00 m
Talveg level	6.00 m
Height above Talveg	28.00 m

Fread first developed the Breach model used in this study, which is among the models used today to determine the breach that can occur in a dam and the characteristics of the breach, in 1977. The model got its latest shape in 1991 after having gone through a number of modifications (Sakkas and Strelkoff, 1976; Fennema and Chaudry, 1987; Fread, 1998). The Breach model is a mathematical model used to determine the dimensions, duration of occurrence of the breach and the overflow hydrograph coming out of the breach. The Breach model is physically based on hydraulic principles, carriage of solid substances, surface mechanics, dam geometry, properties of the dam material, features of the dam reservoir and the amount of inflow entering the reservoir depending on the time.

The main difference of the Breach model developed by Fread from the previous versions is the absence of a parametric approach unlike the previous ones; that is to say, empirical conclusions were not drawn taking the failed dams as a basis. The latest Breach model depends on the use of qualitative parameters of the dam that can be estimated or measured. However, one has to mention that even though measurable parameters are used, there is a likely distribution among the parameters. This distribution affects the size of the overflow hydrograph coming out of the breach and the duration of breach formation. Therefore, hydrologists and engineers must carry out sensitive analysis and measurement in areas where the dam material is most critical.

If the dam body to be studied does not consist of homogeneous material, features of the materials that have to be considered for the Breach model are shown in Table 2. This table shows the parameters of the materials in both the outer section of the body and the inner core as well as the characteristic data that have to be considered for the model. Apart from the specified characteristics of the materials, if the surface of the downstream side is vegetated, then the quality of the grass has to be taken into consideration.

Table 2 Features of the materials to be considered in the Breach model

Parameters related to the material	Characteristics related to the structure
a) Internal friction angle	a) Downstream and upstream slope of dam
b) Cohesion stress	b) River bottom slope
c) Mean grain diameter (D_{50})	c) Crest level and weight
d) Density	d) Spillway level and capacity level
	e) Inflow hydrograph
	f) Reservoir surface-area curves
	g) Initial surface level

In the destruction caused by overflow of water over the body, the water surface spot height of the reservoir must exceed the top spot height of the body without any attrition. In such failures, formation of a breach starts in the upstream side of the dam first and the breach that is formed progresses towards the downstream side along the crest width of the dam. In the model used, water coming out of the breach is obtained by means of a sluice formula and the width of the formed breach is assessed as dynamic. The changes occurring in the reservoir during the formation of the breach is dealt with by the principle of protection of the mass.

Numerical model for flood routine

The overflow flood routine model FLDWAV used in modelling the overflow wave occurring upstream after the collapse of the dam was developed by NWS (National Weather Service). FLDWAV includes not only the combined properties of the former DAMBRK and DWOPER overflow flood routine models but also the new hydraulic simulation properties.

Risk assessment by means of GIS

River basin and coastal management relies on an appreciation of the complex nature of the environmental processes. Clear understanding requires the modelling of these processes, which in turn calls upon a large number of disparate data sets. The most effective way to model these data, facilitate analysis, and allow clear visualisation, is by geographical position. This paper describes a system which improves the efficiency and applicability of coastal processes in support of shoreline management decisions.

In connection with territorial management activities, potential risks to the population and risks for costly material damages need to be assessed. Risk assessments are also sometimes carried out as part of the design of new facilities. Various types of risk assessment may be carried out using GIS and conventional modelling techniques together. In this study one of the possible risks, flood prediction is assessed. An emergency management needs planning and training activities. GISs are nowadays widely used by authorities at regional and municipal levels. When such systems are taken into full use, basic registers are connected to GISs and thereby all population, building, tenement and property information can be managed directly from the map. In the area of emergency management, planning and training risk assessment calculation form the basis for decision making. When the calculations are linked to geographical information, it is much easier to rescue people who are at risk (Heino and Kakko, 1998).

Geographic Information Systems provide an extensive approach to evaluate map characteristics that explain the spatial distribution of the study area. GISs have the capability of spatially representing data on the land surface and linking additional data related to this spatial depiction through tables and charts as well as maps. In this study a decision support system was developed for a dam break. In this study a hydrologic model was linked together with a geographic information system to simulate a possible dam break and its effect on the area.

Application

In the Fldwav model, certain topographic data about the area where the dam is located and the downstream bed of the dam are needed. Topographic data in the form of 1/5,000-scale digital maps have been obtained from the Istanbul Metropolitan Municipality. Using digital elevation data and by means of the ArcView Geographical Information System, a digital terrain model was formed. As seen in Figure 1 a total of 10 cross-sections along the valley lying downstream of the dam were obtained in this model.

The distance of the first cross-section to the dam is 0.273 km and the last one is 5.162 km. As a sample section, Figure 1 shows the section that is 1.045 km away from the dam. Manning coefficients used in cross-sections have been determined by going around the downstream of the dam and making use of a table of Manning values according to Chow's surface features.

Scenario of the dam collapse due to overflowing of water over the dam body

Before examining the scenario of the dam collapse due to overflowing of water over the dam, it was studied to see whether the full sluice capacity was adequate or not for different water levels in the reservoir when there is an overflow with a 1,000-year return period. During the first stage, when we examined the case of water level spot height in the reservoir at 26 m and the spillway hatches were open, it was observed that the water level did not exceed the dam body therefore no breach was formed. Later on, when the same process was repeated under similar circumstances but at different water levels of 28 m, 30 m and 32 m respectively, no breach formation was observed in the body of the dam. Even when the water level in the reservoir is at the maximum, the spillway capacity was found to be adequate.

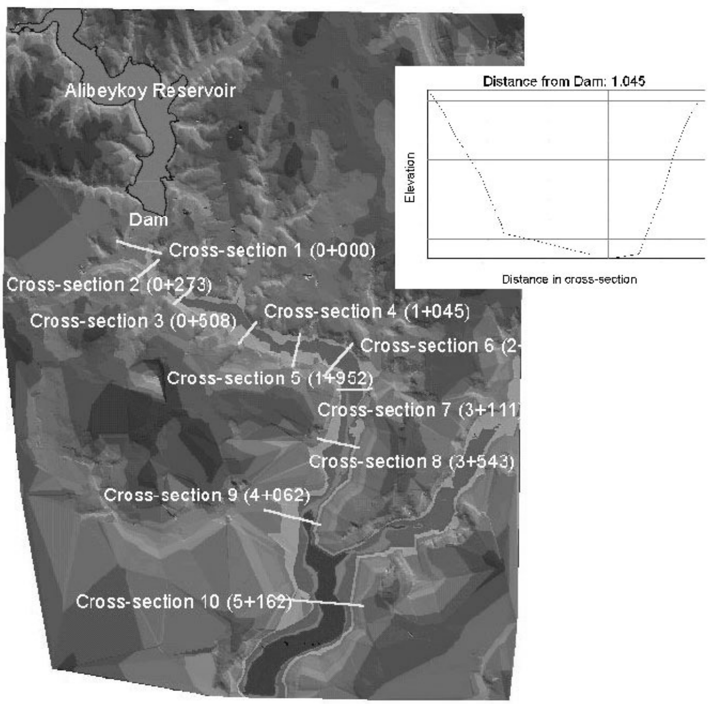

Figure 1 Digital terrain model produced by means of GIS and the cross-sections taken on it, and the cross-section 1.045 km away from the dam

Table 3 Water levels (m) at the cross-sections after a dam break

Time (hour)	1	2	3	4	5	6	7	8	9	10
2.74	34.16	8.18	7.43	5.96	5.51	4.8	4.13	3.4	2.9	1.37
2.80	34.15	9.47	8.53	6.19	5.55	4.83	4.15	3.42	2.92	1.38
2.85	34.12	10.75	9.71	7.15	5.66	4.85	4.17	3.44	2.94	1.38
2.90	34.06	12.11	10.97	8.68	6.38	4.88	4.18	3.47	2.96	1.39
2.95	33.95	13.62	12.39	10.35	7.9	5.14	4.2	3.5	2.98	1.41
3.0	33.78	15.3	13.95	12.07	9.69	6.32	4.32	3.52	3.01	1.42
3.05	33.54	17.02	15.53	13.88	11.63	8.05	5.47	3.63	3.03	1.43
3.10	33.2	18.7	17.06	15.67	13.41	10.14	7.48	5.3	3.19	1.45
3.15	32.76	20.41	18.62	17.39	15.03	11.92	9.74	8.1	5.93	1.47
3.20	32.2	22.11	20.17	19.01	16.5	13.45	11.78	10.93	9.24	1.79
3.25	31.51	23.76	21.65	20.53	17.84	14.93	13.9	13.11	11.61	5.46
3.30	30.68	24.95	22.85	21.84	19.07	16.53	15.71	14.89	13.49	8.64
3.35	29.86	24.65	22.85	22.04	19.55	17.62	17.07	16.31	13.83	10.73
3.40	29.09	24.2	22.56	21.72	19.57	18.03	17.57	16.92	15.9	12.05
3.45	28.36	23.7	22.19	21.4	19.5	18.15	17.73	17.13	16.19	12.56
3.50	27.68	23.21	21.82	21.08	19.34	18.11	17.69	17.11	16.22	12.73
3.55	27.02	22.75	21.45	20.74	19.11	17.94	17.53	16.98	16.11	12.76

In order to see the consequences of overflowing of water over the dam body, the situation of the water level in the reservoir at 34 m and the spillway hatches closed was examined as an extreme case.

When calculating the breach characteristics of the Breach model, it has been assumed that the formation of the breach started once the water level in the reservoir reached 34.16 m. For lower values, it has been assumed that the water exceeded the dam body without causing any harm to the body of the dam. Breach characteristics thus obtained were; 0.63 hour as the duration of breach formation, 240 m as the top width of the breach and 25 m as the base width, respectively. In the Fldwav model used for the overflow flood routine occurring as a result of breach formation, the 1,000-year overflow hydrograph was taken as the upstream border condition.

When calculating the duration of breach formation, the time interval was selected to be $\Delta t = 0.01$ hour and the distance interval to be $\Delta x = 0.01$ km. For the results obtained for the scenario of water exceeding the dam body, water surface spot heights in the sections used at the application for $t = 2.74$ hours and $t = 3.55$ hours time intervals are given in Table 3. As a result of the calculations, it has been observed that the water level in the dam reservoir reached the level of 34.16 m after $t = 2.74$ hours and the peak value of the output overflow coming out of the breach was $t = 3.30$ hours. As a result of this failure scenario, the maximum water level spot height in the section which is farthest from the dam (5.162 km) reaches the value of 12.76 at the time of $t = 3.55$ hours. As the total duration of the 1,000-year overflow hydrograph is 72 hours, the observation period was selected to be 100 hours when analyses were made. The maximum surface spot height was calculated as 3.84 m at the time of $t = 20.57$ hours in the section which is the farthest from the dam.

Conclusions

In this study, the breach and the hydrograph of the overflow out of the breach occurring in case of an overflow of water over the body of an earth-filling dam have been determined and the flood routine of this overflow in the downstream bed was made numerically and risk maps were obtained with the integration of new methods.

By using ArcView software, the water distribution in the downstream for the times of $t =$ 3.05 hours and $t = 3.55$ hours, is calculated and results given in Figure 2. Distribution of water is also given in the middle as a 3D view of the study area, with the aerial photograph

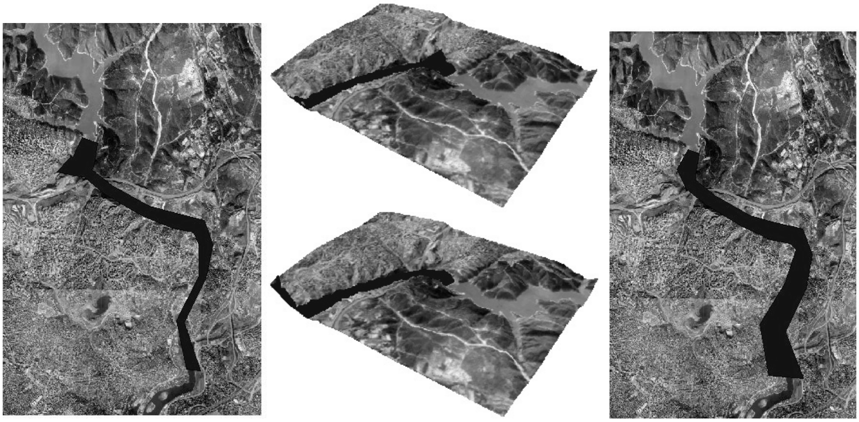

Figure 2 Distribution of water on the downstream side of the dam at the time of t = 3.05 hours and of t = 3.55 hours of the flood due to overflow of water over the dam body

of the same area. As it can be understood from the figures and the tables, in the event of an overflow of water above the dam body, the areas lying on the downstream side of the dam will quickly be under water. Therefore, as mentioned above, such studies have to be carried out for all the dams in order to determine urgent prevention plans and flood maps.

- It has been shown that Geographical Information Systems can be widely and successfully used in determining the risk maps.
- They can further be used in setting up early warning systems. It can be said that the cost of setting up an early warning system in all the dams throughout the country would be less than the cost that would incur after a dam failure.
- As by means of overflow routine calculations, change in output of the flood and water level can be calculated, and dimensions of the flood prevention structures can be safely determined.
- When the overflow hydrograph entering the lake is known, the output leaving through the spillway can be calculated by the flood routine. As a result of these studies, size of the spillway, height of the cofferdam, highest water level in the dam lake, height of the dam and the soil that will submerge under the dam lake are determined.
- Besides being rather costly structures**,** the dams, when destroyed, would lead to large-scale material and moral loss. Therefore, such calculations should be applied to all structures.

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