Numerical simulation of dam-breach flood waves

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Abstract
Dam breach due to the earthquake, Land sliding inside the dam reservoir, dam overtopping as a result of intense precipitation in a watershed are examples of dangerous risks which flood caused by any of them should be predicted by suitable hydraulic or numerical models in the framework of a risk management plan. In the present research, 2DHec-Ras model has been applied in order to flood modeling of Sattarkhan dam. This dam is in the North West of Iran, located 15 km from the west of Ahar city, in the East Azerbaijan province, Iran. The downstream part of the dam to Ahar city has been studied considering the population and infrastructures in this district according to two different scenarios of dam failure. The first scenario includes piping of flow and dam failure profile with steep side walls while the second scenario consists of inclined sidewalls in the dam breach profile and overtopping of flow as the main cause of breaching. The population centers have been selected in the downstream area of dam according to the field facts. The maximum flood depth reaches up to 9.1 m for the first scenario and 7.1 m for the second scenario at the Islamic Azad University and Tabriz-Ahar road, respectively. The results show the notable risk for some of the population centers in the downstream of the dam. Furthermore, the arrival time of flood, recession time, and maximum velocities in the targeted areas for preparing emergency action plans has been calculated.

Keywords Dam-breach · Flood wave · Piping · Overtopping · 2DHec-Ras

Introduction
Every man-made interference in the environment usually leads to a source of risk. Even though implementing development projects is needed for further accessing to water resources, neglecting the risk of water resource projects is a strategic mistake which causes probable disaster in the future. Construction and operation of dams are one of the mentioned development projects which require careful attention to deal with relevant risks.

Various phenomena such as flood waves and land inundation caused by run-up wave, dam break wave, etc. cause human and financial losses, so modeling and ways to overcome them is a necessary thing that has been done by various researchers (Ziaadini-Dashtekhaki et al. 2021; Hosseinzadeh-Tabrizi and Ghaeini-Hessaroeyeh 2017). In the dam failure phenomenon, long time and short time-saving activities depend on the prediction of the flood (Hosseinzadeh-Tabrizi and Ghaeini-Hessaroeyeh 2018). Dam breach due to the earthquake, Land sliding inside the dam reservoir, dam overtopping, or piping in the downstream as a result of intense precipitation in a watershed or a mistake in the implementation or design phases are examples of dangerous risks. Therefore, flood caused by any of the mentioned risks should be predicted by suitable hydraulic or numerical models in terms of a risk management planning process. All applied models for the mentioned purpose should consider the number of important factors such as breach theory or in general, gradual failure of the dam, distance of the dam from population centers, critical industrial and educational and residential centers in the path of the torrential flow and also the types and the number of other hydraulic structures on the way of flood in the downstream. Then the results of the applied model including inundation probability map, the conditions of inundation, and the estimation of impact on the number of victims and infrastructure (Juliastuti et al. 2019) can be used for each prediction aimed at preparing an Emergency Action Plan (EAP).

Because of limitation and cost of hydraulic models, the numerical models are widely used aimed at preparing EAP. For example, Sanders (2007) worked on evaluating online
Digital Elevation Models (DEMs) which were being used for modeling of flood inundation. He compared many types of DEMs in a comparative evaluation. It is concluded the advantage of using shuttle radar topography mission DEMs.

Basnayaka et al. (2011) apply two different numerical modeling approaches named hydraulic two-dimensional surface and hydrological surface routine approaches aimed at surveying the risk of an urban catchment. Their study showed that the results of hydrological surface routing are more acceptable than the other numerical model.

Chandrabose and Nair (2014) implemented a dam breach analysis for Malankara dam using Hec-Ras and Hec-GeoRas models. They simulated the probable maximum flood and the travel time of flood waves. Sharma and Mujumdar (2016) prepared a scenario of breaching of Ajwa Dam applying Hec-GeoRas and Hec-Ras models. They presented floodplain inundation map for downstream part of the dam. Balaji and Kumar (2018) used 1D-Hec-Ras model for dam breach analysis of Kalyani dam constructed across Swarnamukhi River; they introduced their study as a tool for providing emergency plan. Lea et al. (2019) simulated the Beaksan levee breach in Korea using 1D-2D Hec-Ras coupled model aimed at being ready for similar flood events in the future. Hutanu et al. (2020) compared 1DHec-Ras model using Lidar images with other implemented research deployed MikShe model in the north-eastern of Romania. They concluded that Hec-Ras model results provided more realistic prediction of flood than the MikShe model. Psomiadis et al. (2021) studied Bramianos dam in Crete island of Greece using Hec-Ras model and digital surface model (DSM) and DEM taken from high-resolution images in a comparative approach. Salman et al. (2021) worked on another case using Hec-Ras model. They used Geographic Information System (GIS) and applied different return periods of flooding in three watersheds and found the most vulnerable area.

According to the past researches, it is needed to deal with flood mapping especially in a semi-arid country such as Iran because on one hand numerous dams has been constructed in this country, and on the other hand, Iran located on the earthquake line. Therefore, the evaluation of downstream part of Sattarkhan dam in the northwest of Iran near the Ahar city in terms of dam breach-induced flood have been targeted in the present study using Hec-Ras model. The model is one of robust tools for numerical modeling. Hec-Ras model has been deployed for the study of probable dam failure of the Sattarkhan Dam. Other software such as ArcGis, Global Mapper, and Google Earth have widely been deployed in the study for providing DEM from satellite images and analyzing the results, and presenting them. The populated and significant centers have been selected in the downstream part of the dam due to relatively accurate survey of satellite images. In the present study, the comparative study has been done including two scenario of dam breach by two breaching profile of the dam, considering piping and overtopping failure. Then according to the numerical flow modeling, the significant hydraulic factors of flood such as maximum flow velocity, arrival and recession times, and flow depth are calculated.

### Governing equations

The governing equation consists of the shallow water equations which are used in the vector form as follows (Xia et al. 2010):

\[
\begin{align*}
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} &= 0 \\
\frac{\partial (uh)}{\partial t} + \frac{\partial (u^2h^2 + gh^2/2)}{\partial x} + \frac{\partial (uvh)}{\partial y} &= 0 \\
\frac{\partial (vh)}{\partial t} + \frac{\partial (uvh)}{\partial x} + \frac{\partial (v^2h^2 + gh^2/2)}{\partial y} &= 0
\end{align*}
\]

\[
\frac{\partial U}{\partial t} + \nabla F(U) + \frac{\partial (U)}{\partial x} + \frac{\partial (G(U))}{\partial y} + \frac{\partial (F(U))}{\partial y} + \frac{\partial (G(U))}{\partial y} = S(U)
\]

\[
U = \begin{bmatrix} u \\ uh \\ uh \\ u^2h^2 + gh^2/2 \\ uvh \\ uvh \\ v^2h^2 + gh^2/2 \end{bmatrix}, F(U) = \begin{bmatrix} uh \\ u^2h^2 + gh^2/2 \\ uvh \\ u^2h^2 + gh^2/2 \\ u^2h^2 + gh^2/2 \\ u^2h^2 + gh^2/2 \end{bmatrix}, G(U) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

where \( t \) is the time; \( h \) the water depth; \( u \) and \( v \) the depth-averaged velocity components in \( x \) and \( y \) directions; \( g \) the gravitational acceleration. The source term vector is calculated as follows (Soares-Frazao and Zech 2011):

\[
S(U) = \begin{bmatrix} gh(S_{0x} - S_{f_x}) \\ gh(S_{0y} - S_{f_y}) \end{bmatrix}
\]

where \( S_{0x} \), \( S_{0y} \) are the bed slope in the \( x \) and \( y \) directions respectively; and \( S_{f_x} \), \( S_{f_y} \) are the friction slope components.

### Numerical modeling

#### Study area

The downstream of Sattarkhan dam to Ahar city has been surveyed as study area which is shown in Fig. 1. The total area of computational domain in the downstream of Dam is 442.66 km\(^2\). Figure 1 shows the mesh of this area and also, the location of upstream and downstream boundaries. The total number of quadrilateral cell considered in the study area is 43960 cells.

There are many important industrial and residential centers in this area that their locations are observed in Fig. 2. Therefore, the time of flood arriving caused by each dam...
A breach scenario has been calculated and presented for each center in the following section.

**Breaching, initial and boundary conditions**

In this modeling, the water level in the Sattarkhan reservoir while breaching is 1454 m as initial condition (maximum water level) according to dam’s operation and maintenance instruction. Two Boundary Conditions (BC) have been defined in the upstream and downstream of 2D area. The upstream BC is Sattarkhan Dam, as connection between reservoir and 2D area and the downstream BC is the “Normal Depth” that means river flows under uniform flow conditions at the downstream boundary of the model (Hec-Ras River and analysis system user Manual 2016). The computational time interval in the model is 1 s.

Also, two scenarios for dam breach are considered. In the first scenario, gradually breaching resulted from piping has been considered (Brunner 2014). The width of the breach is 200 m out of the total width of the dam, 350 m. The breach pattern is presented in the Fig. 3 as follows:

In the second scenario, the gradually dam failure is caused by overtopping (Brunner 2014). The breaching profile is shown in Fig. 4 which is different of the first scenario breaching profile.
Results

Maximum water depth (MWD) and maximum velocity

The inundated area in the downstream part of Sattarkhan dam caused by the first and the second scenario along the populated, residential, educational and industrial centers are observed in Fig. 5a, b. The maximum flow depth and maximum flow velocity are presented in Table 1 for each center in the downstream of Sattarkhan dam.

As it has been presented in Table 1, the residential and educational centers named Gavanjik and Oshtologh villages and Ahar Islamic Azad University significantly been affected by dam-breach flooding and some parts of those centers have been inundated in both scenarios. The Maximum Water Depth (MWD) caused by dam-breach in Gavanjik and Oshtologh villages and Ahar Islamic Azad University reach to 3.8, 3.2, and 9.1 m for the first scenario and 5, 1.2, and 6.9 m for the second scenario, respectively. The road of Tabriz-Ahar (the first part of the road where flood arrives) is another important infrastructure. The related MWD for this road is 3.6 m for the first scenario and 7.1 m for the second scenario. Except a small part in the south of Ahar city, other parts of this city have not been affected by flood, also Ahar industrial zone has almost been far from the flood. Furthermore, other important infrastructures, including Main Bridge (Entrance), Sub-bridge1 and Sub-bridge2 are at risk of flood water waves with heights of 5.9, 5.8, and 6.5 m for the first scenario and 3.9, 4.1, and 4.7 m for the second scenario, respectively.

One of the significant hydraulic factors affects on downstream infrastructures and residential areas are the maximum velocity. This factor mainly links to soil scouring which plays important role in terms of safety of infrastructures and also safety of populated areas. The Maximum velocities of flood caused by Sattarkhan dam breach have been presented in Table 1 and Fig. 6 for each scenario.
One of the most effected part of infrastructures due to flood caused by dam breach is the road of Tabriz-Ahar. The maximum velocity in this area reaches to 3.7 m/s. Therefore, a massive destruction can be predicted in the related structures, and also soil erosion will be considerable.

The maximum velocity of flood in the main bridge (entrance), sub bridge2, sub bridge 1, Ahar Islamic Azad University, Gvanjik village reaches to 5.3, 5.2, 4.7, 4.3, and 4.3 m/s for the first scenario and 4.1, 3.8, 3.6, 4.1 and 6.5 m/s for the second scenario respectively. These flow velocities can lead to massive devastation of related infrastructures and houses around the mentioned centers. These risk factors should be considered in terms of people’s lives along with probable financial damages.

The south part of the Gavanjik village located near the dam should be considered as the most affected part compared to other centers in terms of the bed erosion due to the maximum velocity of 6.5 m/s in the second scenario. According to Fig. 6, in terms of the maximum water depth, except centers of 1 and 2, in the other centers, the first scenario is determinant.

### Arrival and recession times

The depth threshold assumed to be zero in the current study. The maximum flow velocities in the downstream part of Sattarkhan dam caused by partial and gradual dam breach for the first and second scenarios are shown in Fig. 7. The arrival time is a computed time from a specified time in the simulation when the water depth reaches a specified inundation depth (Hec-Ras user manual 2016) and the recession time is a computed time from a specific time in the simulation when the water depth recedes back below a specified inundation depth (Hec-Ras user manual 2016). The depth threshold assumed to be zero in the current study. The arrival and recession time of flood for each center in the downstream of Sattarkhan are presented in Table 2 and Figs. 8 and 9.

According to Table 2 and Fig. 8, the Arrival Flood Times (AFT) as vital time deployed by emergency plan for Gavanjik and Oshtologh villages and Ahar Islamic Azad University are 19.2, 32.4, and 39.6 min for the first scenario and 16, 30.6, and 42 min for the second scenario, respectively. The

| Center number | Name of the center                | Maximum flow depth (m)-the first scenario | Maximum flow depth (m)-the second scenario | Maximum velocity of flow (m/s)-the first scenario | Maximum velocity of flow (m/s)-the second scenario |
|---------------|-----------------------------------|-------------------------------------------|-------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| 1             | Gavanjik village                  | 3.8                                       | 5                                        | 4.3                                              | 6.5                                              |
| 2             | Road of Tabriz-Ahar               | 3.6                                       | 7.1                                      | 3.1                                              | 3.2                                              |
| 3             | Oshtologh village                 | 3.2                                       | 1.2                                      | 0.9                                              | 1.5                                              |
| 4             | Ahar Islamic Azad University      | 9.1                                       | 6.9                                      | 4.3                                              | 4.1                                              |
| 5             | Main bridge (Entrance)            | 5.9                                       | 3.9                                      | 5.3                                              | 4.1                                              |
| 6             | Sub-bridge1                       | 5.8                                       | 4.1                                      | 4.7                                              | 3.6                                              |
| 7             | Sub-bridge2                       | 6.5                                       | 4.7                                      | 5.2                                              | 3.8                                              |
| 8             | South of Ahar city                | 1.1                                       | 0                                        | 1.5                                              | 0                                                |

Fig. 6 The maximum flow depth for each center in the downstream of Sattarkhan dam for each scenario

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**Table 1** The maximum flow depth and maximum flow velocity for each center in the downstream of Sattarkhan Dam for each scenario

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Arrival and recession times

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AFT while the first region of the road has been inundated by flood is 27 min for the first scenario and 25.2 min for the second scenario so the arrival flood times to reach the mentioned locations is short and requires much more attention. Gavanjik Village and Road of Tabriz-Ahar are the first places that inundated by flood. Furthermore, flood reaches to Ahar Islamic Azad University as one of populated areas in the study region, only within 39.6 min for the first scenario and 42 min for the second scenario. According to Table 2 and Fig. 9, the recession time of flood as an important factor

![Fig. 7](image_url)

**Table 2** The arrival and recession time of flood for each populated, residential, educational and industrial center in the downstream of Sattarkhan dam for both of scenarios

| Center number | Important center name                  | Arrival time of flood (minutes)-first scenario | Arrival time of flood (minutes)-second scenario | Recession time of flood (minutes)-first scenario | Recession time of flood (minutes)-second scenario |
|---------------|----------------------------------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 1             | Gavanjik village                       | 19.2                                          | 16                                              | 45                                              | 27                                              |
| 2             | Road of Tabriz-Ahar                    | 27                                            | 25.2                                            | 84                                              | 36                                              |
| 3             | Oshtologh village                      | 32.4                                          | 30.6                                            | 102                                             | 54                                              |
| 4             | Ahar Islamic Azad University           | 39.6                                          | 42                                              | 180                                             | 180                                             |
| 5             | Main bridge (Entrance)                 | 48                                            | 52.2                                            | 180                                             | 180                                             |
| 6             | Sub-bridge1                            | 56.4                                          | 61.8                                            | 180                                             | 180                                             |
| 7             | Sub-bridge2                            | 62.4                                          | 68.4                                            | 180                                             | 180                                             |
| 8             | South of Ahar city                     | 64.2                                          | –                                               | 117                                             | –                                               |
of planning for saving people’s life for the populated centers of Gavanjik and Oshtologh villages and south of Ahar city are 45, 102, and 117 min for the first scenario respectively and this times for centers of Gavanjik and Oshtologh villages are 27 and 54 min (The south of Ahar city is not inundated by flood). This time for the road of Tabriz-Ahar is 84 min for the first scenario and 36 min for the second scenario. The recession time for the rest of the targeted centers is 3 h. Therefore, it can be resulted that the first moments before arrival of the flood are very important since, after those times, there will be much difficult to save peoples life with due attention to recession times for each center.

Comparing the results of two scenarios in Fig. 8 and Fig. 9 containing the arrival times and the recession times can result the fact behind the nature of breaching model in two scenarios. In the first scenario with piping of flow and steep sidewalls of breaching profile, the strong waves reach to target area earlier in the centers near the dam and according to Fig. 7a the maximum flow velocities resulted from the mentioned waves are bigger than the second scenario in the same centers (Fig. 7b) and they inundate the larger area and there is an expectation of bigger recession time in those centers which has been presented in Fig. 9. In the first scenario, moving forward from Sattarkhan dam to the downstream, as the energy of flood has been depreciated and also, the flood extended in the bigger aria so the arrival times of flood in the second scenario are bigger in the rest of centers (relatively far from the dam) compared to the first scenario.

According to discussion on different aspects of both scenarios of dam breaching, the results of the model should be efficiently deployed for planning vital measures in the framework of EAP. Therefore, the important planned activities can be as follows:

- Providing suitable information broadcast and measures according to the AFTs for each center.
- Considering preventive and safe structures around important centers that the effect of flood caused by dam-breach will be decreased.
• Avoiding extension of Ahar city in the south part and preventing from building structures inside riparian zone of Ahar River.

Conclusion

A 2D Hec-Ras model has been deployed for modeling, dam partial and gradual failure in the Sattarkhan dam in the northwest of Iran using Arc GIS, Global Mapper, Google Earth software, and satellite images.

The populated and significant centers have been selected in the downstream part of the dam due to relatively accurate survey of images and negotiation with manager of operation and maintenance authority of Sattarkhan dam. A comparative study has been implemented in order to reach relatively realistic simulation, two different failure types including piping and overtopping linked to different breaching profile have been considered. Studying of the residential and industrial centers and infrastructures in the downstream part of the dam demonstrates inundation risk approximately for all major centers by flood induced by dam breach. However, Ahar city approximately has good location in terms of flooding caused by dam-breach, and except a small part in the south of this city, other parts located far from the flood. The Islamic Azad University is highly in danger of flood caused by probable Sattarkhan dam breach. The highest flood depth in this center reaches up to 9.1 and 6.9 m for the first and second scenarios, respectively. Therefore, preventive actions will be needed in this important center. The maximum velocity in both scenarios in the studied centers changes between 0.9 and 5.3 m/s that indicate notable erosion risks. The maximum water depths and flow velocities and flood arrival and recession times, which have been calculated in the present model, should be considered in emergency action plan.

Although the current study’s results provide a reasonable prediction of probable disaster, in order to completing of the current study, other scenarios of Sattarkhan dam breach and considering bedload movement in the model can be implemented in the future study. Therefore, in that case, the resulted EAP will be more reliable.

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Declarations

Conflict of interest This article has been submitted to the journal with the full authors consent and agreement. All authors have participated in (a) analysis and interpretation of the data, (b) drafting the article or revising it critically for important intellectual content, and (c) approval of the final version. This manuscript has not been submitted to nor is under review at, another journal or other publishing venue. The following authors have affiliation with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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