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HYDROGEOLOGICAL UNCERTAINTIES IN DELINEATION OF LEAKAGE AT KARST DAM SITES, THE ZAGROS REGION, IRAN

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Abstract: Leakage from dam reservoirs has been reported in different karst regions of the world. Water leakage occurs through the karst features directly or indirectly. The estimation of leakage locations, path(s), and quantity are subject to error due to uncertainties in the non-homogenous nature of a karst formation, method of study, and limited investigation due to time and cost factors. The conventional approaches for study on the karst development are local boring at the dam site and geological mapping. In this paper, uncertainties associated with conventional hydrogeological approaches are addressed from both qualitative and quantitative points of view. No major solution cavities were observed in boreholes and galleries of some dam sites in the Zagros Region, Iran, but huge karst conduits were discovered during the drilling of a diversion tunnel. This inconsistency is due to the point character of boreholes and the inherent non-homogeneity of karst. The results of dye tracing tests in boreholes may be significantly affected by location of the injection and sampling points, as tests executed at the Saymareh and Tangab Dam sites in the Zagros Region, Iran show. The quantitative uncertainty of leakage is analyzed for diffuse and conduit flow systems for cases with and without any grout curtain, under the combined effect of input uncertainties at the Tangab Dam site, southern Iran. Assuming a diffuse flow system, the mean leakage at 95% confidence interval for both strategies is estimated at less than 5% of the mean annual discharge of the river. Accordingly, the dam can be constructed without the necessity of a grout curtain. However, assuming a conduit flow system, the results reveal a significant uncertainty. A small diameter conduit can convey significant amounts of water under high reservoir pressure heads. The leakage of a 4 m diameter conduit (cross section area of 12.5 m^2) is 163 times more than the leakage of 0.5 m diameter conduit (cross sectional area of 0.2 m^2) while the cross sectional area ratio is 60. The uncertainty may be decreased if a detailed study is carried out on the stratigraphic and tectonic settings, karst hydrogeology, geomorphology, speleogenesis, and by performing several dye tracing tests, especially outside the proposed grout curtain area.

Introduction

Leakage from dam sites has been reported in numerous dams in karst areas. Solution activity forms conduits of unpredictable dimensions and geometry whose permeability is often measured in centimeters or meters per second. In most cases, the leakage occurs during the first filling and reservoirs may fail to fill despite an extensive investigation program and sealing treatment. Milanović (1997) reported the maximum leakage from reservoirs in different karst areas of the world. The main causes of leakage at karst dam sites are the non-homogeneous nature of the karst formations, inadequate data, limited investigation due to time and cost limitations, and unreliable models. The high permeability zones are local, representing a small percentage of the total karst area. The risk component may be unavoidable in spite of very detailed and complex investigation programs, including all available methods. It is not realistic to plan complete elimination of risk in karst areas. Therefore uncertainty analysis is a useful technique in assessment of dam safety issues due to leakage.

Yen and Tung (1993) and Tung (1996) classified the uncertainties into natural, model, parameter, data, and operational ones. Natural uncertainty is associated with the inherent randomness of natural processes. Model uncertainty reflects the inability of the model to accurately represent the system's true physical behavior. Models ranging from simple empirical equations to sophisticated computer simulations are used. Parameter uncertainties result from the inability to quantify accurately the model inputs and parameters. Data uncertainty includes measurement errors, non-homogeneity of data, and an inadequate representation of the data sample due to time and cost limitations. Operational uncertainties include those

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associated with construction, manufacture, deterioration, maintenance, and human factors.

The task of uncertainty analysis is to determine the uncertainty of the system output as a function of uncertainties in the model and the system inputs (Tung, 1996). Furthermore, it offers the designer useful insights regarding the contribution of each stochastic variable to the overall uncertainty of the system outputs. Such knowledge is essential to identify the important parameters to which more attention should be given to have a better assessment of their values, and accordingly, to reduce the overall uncertainty of the system outputs. In general, uncertainty analysis provides an estimate of the uncertainty distribution for selected output, according to the inputs.

The most complete and ideal description of uncertainties is the probability density function of the quantity subject to uncertainty. However in most practical problems, such probability functions cannot be derived or found precisely. Accordingly, in this study, the discrete probability distribution (DPD) is used instead of continuous probability distribution. Another measure of uncertainty is the reliability domain, such as the confidence interval. A confidence interval is a numerical interval with a specific probabilistic confidence. Several techniques can be applied to conduct uncertainty analyses. Each technique has different levels of mathematical complexity and data requirements.

Uncertainty analysis has been used extensively in dam safety risk assessments (Bowles et al., 1998; 1999; 2003; Chauhan and Bowles, 2003). Assessing the uncertainty in the hydrogeological studies of karst dam sites has received less attention. An application of a probabilistic risk analysis to the problem of designing a water retention dike on karst terranes was presented by Steven and Bromwell (1989).

The objectives of this article are (i) qualitative analysis of uncertainties in conventional approaches for obtaining hydrological parameters which affect dam leakage estimation with examples of some karst dam sites in the Zagros region, Iran, and (ii) quantitative analysis of applying the diffuse and conduit flow systems for estimation of leakage at the Tangab Dam site, the Zagros region, Iran, by means of uncertainties of input parameters (e.g., permeability, hydraulic gradient, conduit cross section, and friction factor). The results provide recommendations for minimizing the leakage uncertainty.

Regional Setting

Iran is geologically a part of the Alpine-Himalayan orogenic belt. Five major structural zones, different in structural history and tectonic style, can be distinguished in Iran (Stocklin, 1968): a) The Zagros Range, b) The Sanandaj-Sirjan Range, c) Central Iran, d) East and South-East Iran, e) The Alborz and Kopet-Dagh Ranges. The Zagros Range is divided into the three structural zones of the Khozestan Plain, the Simply Folded Zone (SFZ) and the Thrust Zone (Stocklin, 1968). It is about 12 km thick and mainly made of limestone, marl, gypsum, sandstone and conglomerate. Since Miocene time, it has been folded into a series of huge anticlines and synclines. The SFZ passes northeastward into a narrow zone of thrusting bounded on the northeast by the Main Zagros Thrust Line. A wide variety of lithologies including crushed limestone, radiolarite, and ultra basic and metamorphic rocks have been intensively thrust-faulted in this zone. The width of the thrust zone varies from 10 to 70 km and makes up the highest elevations in the Zagros. Karstic carbonate formations cover about 11% of Iran's land area. The total area of karstified carbonate rocks in Iran is about 185,000 km^2; 55.2% of this in the Zagros (Raeisi and Kowsar, 1997).

Most of the outcropping carbonate rocks are of Cretaceous and Tertiary age. The most important karst features in the Zagros Range are karren, grikes, springs, and, to a lesser extent, caves and dolines. Most of the springs are permanent, and a high percentage of the spring discharges are baseflow. The Zagros Folded Zone is characterized by a repetition of long and regular anticlinal and synclinal folds. The anticlines are normally mountain ridges of limestone, and the synclines are valleys and plains. Most of the karst formations in the Zagros Folded Zone are sandwiched between two impermeable formations, forming broad highland independent aquifers (Raeisi, 2004; Raeisi and Laumanns, 2003).

The general direction of ground-water flow is mostly toward the local base of erosion, parallel to the strike. Karst water discharges as springs or flows into the adjacent alluvium aquifer where a direct connection exists between the alluvium and the karst formation. Several dams are under study in karst areas of the Zagros region, especially in the SFZ. Leakage of water has been reported in several karst dams. Designs of grout curtains are mainly based on the geological maps of the dam sites and borehole data. The complexity of karst aquifers and the problem of leakage after dam construction in the Zagros region imply that an uncertainty analysis is a necessity at the design stage.

Qualitative Analysis of Leakage

The qualitative uncertainty is mainly a response to conventional methods of study in the non-homogeneous karst formation. The main characteristics of karst aquifers are the existence of irregular networks of pores, fissures, fractures, and conduits of various sizes and forms. Such structures with significant physical and geometrical heterogeneity cause complex hydraulic conditions and spatial and temporal variability of hydraulic parameters (Denic-Jukic and Jukic, 2003). Controls in the development of karstic aquifers were discussed by Ford and Williams (1989).

Karst development, especially in the main conduit, is controlled by numerous factors such as geological and tectonic settings, base of erosion, thickness, lithology, precipitation, temperature, and CO_2 pressure. These factors are not the same in different karst regions, such that the location and geometry of the main karst conduits differ even within short distances. Local borings (boreholes, galleries and tunnels) and geological mapping at the dam site are the conventional approaches for study of the karst development, consequently affecting the decision about zone(s) and path(s) of leakage and finally estimation of leakage value by applying a model. Qualitative uncertainties associated with boreholes, geological mapping and model are discussed as follows.

Uncertainties Associated with Borings

Exploration boreholes present a unique technique for evaluation of deeper positions of karst terranes, but they provide information which, in many cases, represents only the area in the vicinity of boreholes. The probability of cavity discovery in a borehole network with 50 by 50 m spacing is 1/2500. Experience is replete with cases of the drill hole that just missed a major cave or similar feature (Merritt, 1995). Some of the case studies include:

- Salman Farsi Dam (Iran): No major solutional cavity was observed along 400 m of one of the galleries, but at its end, a cavity with approximate dimension of 150 × 50 × 40 m was discovered.
- Tangab Dam (Iran): No major karst conduits were discovered in any of the boreholes and galleries, while a huge shaft was discovered during drilling of the diversion tunnel.
- Maroon Dam (Iran): No conduit was discovered along the galleries and boreholes. However, a 3 m opening was discovered in the diversion tunnel. This conduit leaked about 4 $m^3\ s^{-1}$ at the first filling before the grout curtain was completed.
- Kohrang III Tunnel (Iran): In one of the adit tunnels, the sediment in a conduit was washed by high pressure water with 800 L s^{-1} discharge from the adit tunnel inlet. The karst conduits were observed frequently in the adit tunnel; the apertures of active karst conduits range from a few centimeters to more than one meter. The velocity of some water jets exceeds 10 m s^{-1} (Sadr and Baradaran, 2001).

Furthermore, water-table measurements and various hydrologic tests (e.g., Lugeon and dye tracing) were carried out in the boreholes. The results of these studies may have high uncertainty due to nonhomogeneity of karst and borehole characters such as number, depth, location, and arrangement.

Lugeon Test Uncertainty

Measurement of permeability by the Lugeon test is a common application in boreholes. Many problems arise in deriving the permeability from the Lugeon test due to the anisotropy and nonhomogenity of karstified formations because such tests are limited to narrow zones around the boreholes. Uncertainties may exist in the measured permeabilities as follow:

(a) Water must be injected into the isolated section separated by rubber packer. The packer is mechanically, hydraulically, or pneumatically expanded and pressed against the borehole wall. Leakage of injected water around the packer may cause great error in the measured permeability value.
(b) Very often the test at a 5 m section produces unrealistic results because the permeability is an average of the 5 m section. A high permeability zone may be located within a small portion of the 5 m section. The test section may be reduced to 1 m in such a situation to increase the reliability of measurements (Milanović, 2000).
(c) Low permeability at the deepest sections of a borehole cannot be considered as base of karstification, because heterogeneity is a natural characteristic of a karst aquifer.
(d) Borehole construction is limited to the area near the dam body or to the proposed grout curtain area. The critical leakage zones may be located outside the proposed grout curtain area. For example, the permeability of the last boreholes in the right and left embankments in Kowsar Dam site, the Zagros region of Iran, and at the end of most boreholes are quite high. This implies that leakage zones may be situated outside the proposed grout curtain.

Isopotential Uncertainty

Isopotential maps can be prepared by contouring water levels in piezometers. Karst aquifers contain both diffuse and conduit components. The route of major conduit systems is marked by well-defined ground-water troughs (White, 1988). The water-table surface in topologically or structurally complex areas may be quite irregular. The unique feature of a karst aquifer is the rapid response of the conduit system compared with that of a diffuse system. Large dimensions of karst conduits, their good interconnections, high water level gradients, and the high permeability of surface zones enable rapid filling and emptying of karst drains.

A high precipitation rate may fill the conduit system, causing water level rise by tens of meters in a few hours. The ground-water trough fills up, bringing water level in a conduit system to the level of the diffuse water table, or mounds the water above it (White, 1988). It can be concluded that the water table configuration depends on the distance of boreholes to a major drain (conduit), capacity of the drain, and the time of measurement. The probability of a borehole tapping the major conduits is low, because the conduit systems occupy a low percentage of a karst aquifer. Therefore, the water-table configuration (isopotential map) mainly presents the flow in a diffuse system.

DYE TRACING UNCERTAINTY

Although the dye-tracer test is one of the most powerful techniques to determine karst development, it is a point-to-point connection and it is dependent on the location of injection and sampling points (or boreholes). Therefore, major karst conduits may be missed. Estimation of ground-water flow velocity is one of the main goals of tracer tests. Although the equation for estimation of velocity is very simple, extensive uncertainties may exist in the results of dye-tracing tests, as explained below.

Injection Point

In general, the injection point must be connected to a conduit system. Dye injection into a diffuse system may create serious uncertainties in velocity. The injected dye may flow in a diffuse system for a long time and then drain into a conduit. Consequently, the average velocity is calculated between the injection point and the sampling point. The share of travel time through the diffuse system may be significant in the total travel time such that the average velocity reduces to values typical of diffuse flow. An obvious example is the Saymareh Dam, the Zagros region, west of Iran.

An injected borehole with a depth of 254 m was constructed in the northern flank of the Ravandi Anticline. The lithology of the HM28 borehole mainly consists of Asmari karstic limestone from 48 m to the bottom of the borehole. Fifteen kilograms of Rhodamine B (Basic Violet 10) were injected into the deep HM28 borehole. The karst system around the HM28 borehole is diffuse type. Thus, no dye was detected in the sampling points. The following justify the storage of dye around the HM28:

- Calculations showed that the dye could be stored in the vicinity of the HM28 borehole with a minimum concentration of 2759 ppb (Asadpour, 2001).
- The permeability of the HM28 borehole under the water table was less than 10 Lugeon and no conduits were observed in the lithological column of the HM28 borehole below the water table.
- The Gachsaran Formation (consisting of impermeable layers) outcrops in the vicinity of the HM28 borehole, preventing the infiltration of rainwater into the Asmari Limestone and consequently karst is undeveloped.

Sampling Points

The injected dye flows directly or indirectly into a conduit. The dye concentration is higher and travel time is lower in the main conduit compared to the nearby diffuse system. If the boreholes are connected to the diffuse system, the dye may not be detected or the calculated velocity may be in the range of diffuse flow. The connection of boreholes to the diffuse system and the small number of boreholes increase the uncertainty in the calculated velocity. Boreholes (sampling points) are mainly drilled for the geotechnical purposes.

For instance, at the Tangab Dam site, the Zagros region, southern Iran, all the boreholes were located within the diffuse system. The dye concentration in a borehole 50 m away from the injection point and other nearby boreholes were very low with insignificant dye concentration, while the injected dye was detected at high concentration after 5 days in some of the downstream springs about 5 kilometers away from the injection point. It can be concluded that none of the boreholes intersected the conduit transporting the dye. The detected dye in the boreholes was due to dispersion. The calculated velocity in the boreholes is not representative of the conduit system and is subject to uncertainty.

Dye Dilution

The concentration of injected dye may be reduced by the absorption of dye on the contact surface of limestone with the ground water, the decay of dye in darkness, and dilution with ground water. The dye may dilute significantly when it emerges into a big river. It may be absorbed or diluted to such a low level that it cannot be detected by a spectrofluorophotometer. Dye dilution to an undetectable level creates great uncertainty in the results. It implies a false result of no connection between injection and sampling points. The uncertainty can be reduced by increasing the amount of injected dye. For example, ten kilograms of uranine were injected in a borehole on the right abutment of Sazbon Dam site, the Zagros region, Iran (Aghdam, 2004). The dye was not detected in the big river 100 m away from the injection point. It was only detected at very low concentration in three boreholes on the left abutment. The dye may not be detectable in the river and other boreholes in the left abutment, creating uncertainties in the results. The uncertainty can be alleviated with further dye tracing in the left and right abutments.

UNCERTAINTIES ASSOCIATED WITH GEOLOGICAL MAPPING

Although geological mapping is one of the primary techniques to determine the most probable leakage zone in a dam site, it is not capable of predicting conduit locations and probable leakage zones because the karst conduits are small in size and they cannot be identified precisely based on geological maps. The general direction of flow is mainly controlled by bedding-plane partings, concentration and patterns of joints and faults, relief, base of erosion and pattern of folding. There are numerous pathways providing alternative routes for ground-water flow. At the initial stage of karst development, an optimum hydraulic path with least resistance to flow, shortest and steepest route is enlarged out of the large number of all possible alternative routes. Once a conduit is developed, it acts like a drain, and the growth of alternative paths is suppressed while conversely, the conduit aperture is enlarged by continued dissolution.

It is a common theory in Iran that the fault is the only general direction of flow. However, faults may have positive, negative, and neutral effect on ground-water flow and conduit enlargement (Kastning, 1977). Faults often operate hydrologically like major joints. Where large vertical faults are present in a karst area, it is common to find sinkholes and larger landforms aligned along them or close to them, but the situation is variable and less predictable with respect to solution caves. It is comparatively rare to find an entire system of conduits that is controlled primarily by faults or contained within them (Ford and Williams, 1989). Because they are initially mostly widely opened, faults attract migrating solutions during and after deep tectonism. Parts of faults become sealed by the secondary calcite so that, although substantial voids remain elsewhere, they can not be connected to permit ground-water flow along, up, or down the entire fault plane.

Many fault planes are highly impermeable to ground-water flow. Faults are sometimes important in introducing blocks of other lithologies that may act as a barrier to water movement. This may arise from normal or reverse faulting of non-karst rocks or may involve fault plane guided intrusions of igneous material (Ford and Williams, 1989). These impose an impervious curtain across an aquifer, considerably interrupting ground-water flow and aquifer development. Further, the other karst development parameters such as local relief and base of erosion normally exert a greater influence on the direction in which ground-water flows, because hydraulic gradient is strongly influenced by them. It is local relief that determines the lowest points at which ground-water outflow can take place (Ford and Williams, 1989). It can be concluded that the mapping of faults is not enough to determine the direction of ground-water flow and further hydrogeological studies are needed to determine the role of faults on the general direction of flow.

Quantitative Analysis of Leakage

The quantitative uncertainty analysis requires a significant amount of data as input. Data collection for input variables and parameters is extremely expensive and time consuming, particularly in complex non-homogenous karst dam sites.

Various analytic and computational techniques were applied for examining the effect of uncertain input within a model. The effect of changes in inputs on model predictions (i. e., sensitivity analysis), the uncertainty in the model outputs induced by the uncertainties in its inputs, and the comparative importance of input uncertainties in terms of their relative contributions to uncertainty in the output may be considered in uncertainty analysis (Morgan and Henrion, 1990). A drawback of sensitivity analysis is that it ignores the degree of uncertainty in each input. An input that has a small sensitivity but a large uncertainty may be just as important as an input with a large sensitivity but smaller uncertainty. Gaussian approximation is the simplest approach that considers both sensitivity and uncertainty consequently the variance of the output is estimated as the sum of squares of the contributions from each input (Morgan and Henrion, 1990).

However, Gaussian approximation is a local approach in that it considers the behavior of the input function only in the vicinity of the mean or median. Therefore, we need to use a global approach that explicitly evaluates the function (distribution) of each input. Use of discrete probability distribution (DPD) to approximate the uncertainty in output is widely used in decision analysis. It is usual to approximate continuous distribution by discrete distributions with three or five values. Conventionally, the middle value is chosen equal to the median and the other points are chosen roughly to minimize the total area between the continuous cumulative distribution and the stepwise cumulative function representing the discrete distribution (Morgan and Henrion, 1990).

The first step of the DPD approach is to determine the five points of discrete distribution, as illustrated in Fig. 1. The DPD for each input consists of five pairs; each pair is a value and corresponding probability. We then obtain a corresponding distribution for a $\times$ b (Fig. 1), taking the cross products of the values and of the probabilities, obtaining a DPD with $5 \times 5 = 25$ value-probability pairs. In the second step, the DPD for a $\times$ b is condensed; that is, the twenty-five-point distribution is approximated by a five-point distribution. Thus, when using the result to obtain the cross product for a $\times$ b $\times$ c (Fig. 1), the resulting DPD has only twenty-five points, rather than $5 \times 25 = 125$ points.

The quantitative analysis of uncertainty associated with estimation of leakage is studied for two simple one-dimensional flow conditions including diffuse and conduit at the Tangab Dam site by using DPD method. A karst aquifer is classified as having diffuse, conduit, or mixed flow regimes (White and Schmidt, 1966, Shuster and White, 1971, Atkinson, 1977). In a diffuse system, laminar flow occurs through interconnected fissures less than 1 cm in diameter. The flow is turbulent in a conduit system; sizes ranging from 1 cm to more than 1 m. Models ranging from simple empirical equations to sophisticated computer simulations (e.g., Howard and Groves, 1995; Dreybrodt et al., 2002; Kaufmann, 2003; Romanov et al., 2003; Bauer et al., 2003; Liedl et al., 2003) are used. The Darcy equation simulates a diffuse flow system

$$Q = kiA \tag{1}$$

where, Q is discharge, k is permeability, A is total cross

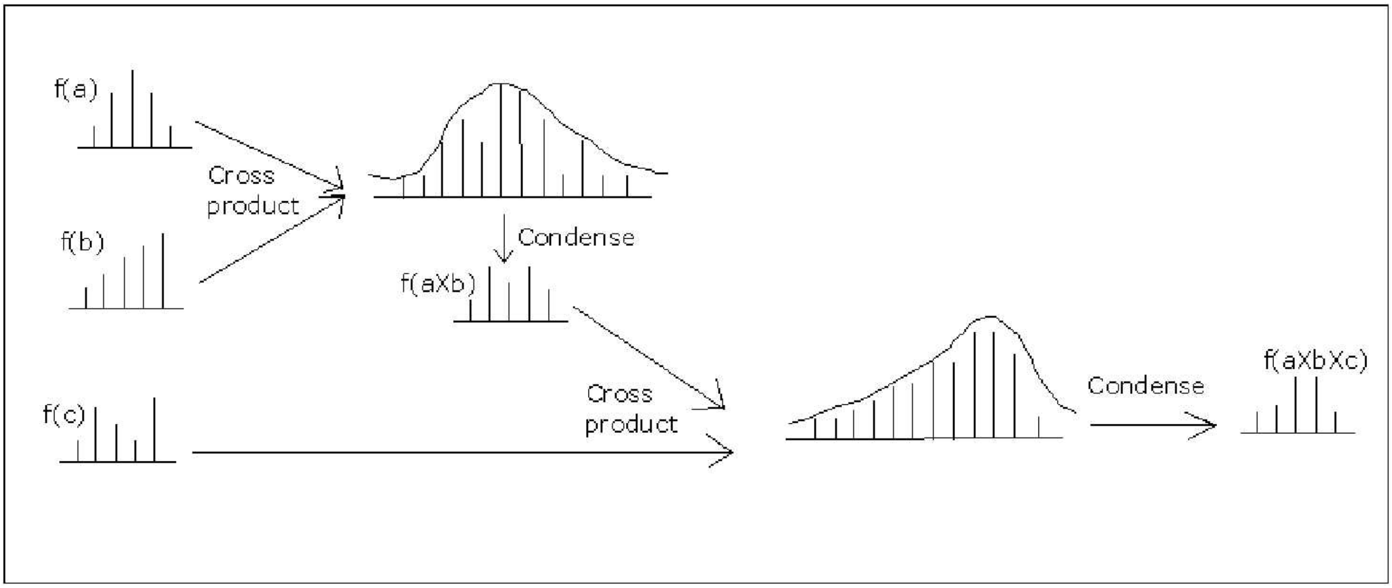

Figure 1. Schematic diagram of the DPD method.

sectional area, and i is hydraulic gradient. The Darcy-Weisbach equation is applicable in a conduit flow system

$$Q = \left[\frac{2dgA^2}{f}\right]^{1/2}[i]^{1/2} \tag{2}$$

where, d is diameter of the conduit, A is the conduit cross section area, g is gravity, and f is friction factor. Most karst aquifers contain both diffuse and conduit flow regimes. It is a very difficult task to determine the percentage of diffuse and conduit flow and the cross section of the conduit. Therefore, great uncertainties exist in model selection.

CASE STUDY

The Tangab Dam is currently under construction in the northern flank of the Podenow karstic anticline, at the entrance of a gorge on the Firoozabad River, about 80 km southeast of Shiraz, the Zagros region, southern Iran (Fig.2). The dam is designed as a rock-fill embankment with clay core (Fig. 3). The technical data are presented in Table 1. The catchment area of the Firozabad River at the dam site is approximately 1356 km^2, and its mean annual flow is 3.8 $m^3\ s^{-1}$. A geological map of the dam site is shown in Figure 2.

The main geological formations consist of Pabdeh-Gurpi (Paleocene-Oligocene), Asmari (Oligocene-Miocene), Transition Zone and Razak (Lower Miocene). The Pabdeh-Gurpi Formation is not exposed at the surface near the dam site nor in the area of the reservoir, but it constitutes a hydrogeologically important aquiclude beneath the Asmari Limestone. The Asmari Limestone forms the walls of the dam site gorge. The core of the Podonow Anticline is composed of the Asmari Formation limestone which is sandwiched between the two impermeable formations that include the Pabdeh-Gourpi (marl, shale and marly limestone) and Razak Formations (silty marl to silty limestone with interbedded layers of gypsum) (Karimi et al., 2005). The thickness of the Asmari Formation in the study area is about 400 m and its contact with Razak Formation is transitional. The thickness of the Transition Zone varies from zero to 300 m, and it is composed of alternating layers of marl, marly limestone and limestone (Karimi et al., 2005).

The hydrogeological setting of karstic springs near the dam site was extensively studied by Karimi (1998) and Karimi et al. (2005). The Asmari Formation constitutes the bedrock at the selected site. The beds dip very gently upstream. Fractures and joints are widely spaced and moderately opened. A minor fault passes to the left of the dam site. No faults were detected in the foundation area of the dam.

The reservoir will be in direct contact with the karstic Asmari Formation in both abutments (Fig. 2). The contact area is 600 m by 200 m in the left abutment and 200 m by 200 m in the right abutment. The geological conditions for construction of the grout curtain also appear favorable. Large voids were not detected (although a few karst features are likely). Therefore, it is expected that adequate seepage control can be obtained by taking the curtain into the marly limestone at depth (about 150 m) and extending it 120 to 150 m laterally into the abutments. The dimensions of designed grout curtain are presented in Figure 4.

No solution cavities or major karst conduits were observed in boreholes or galleries. However, two caves

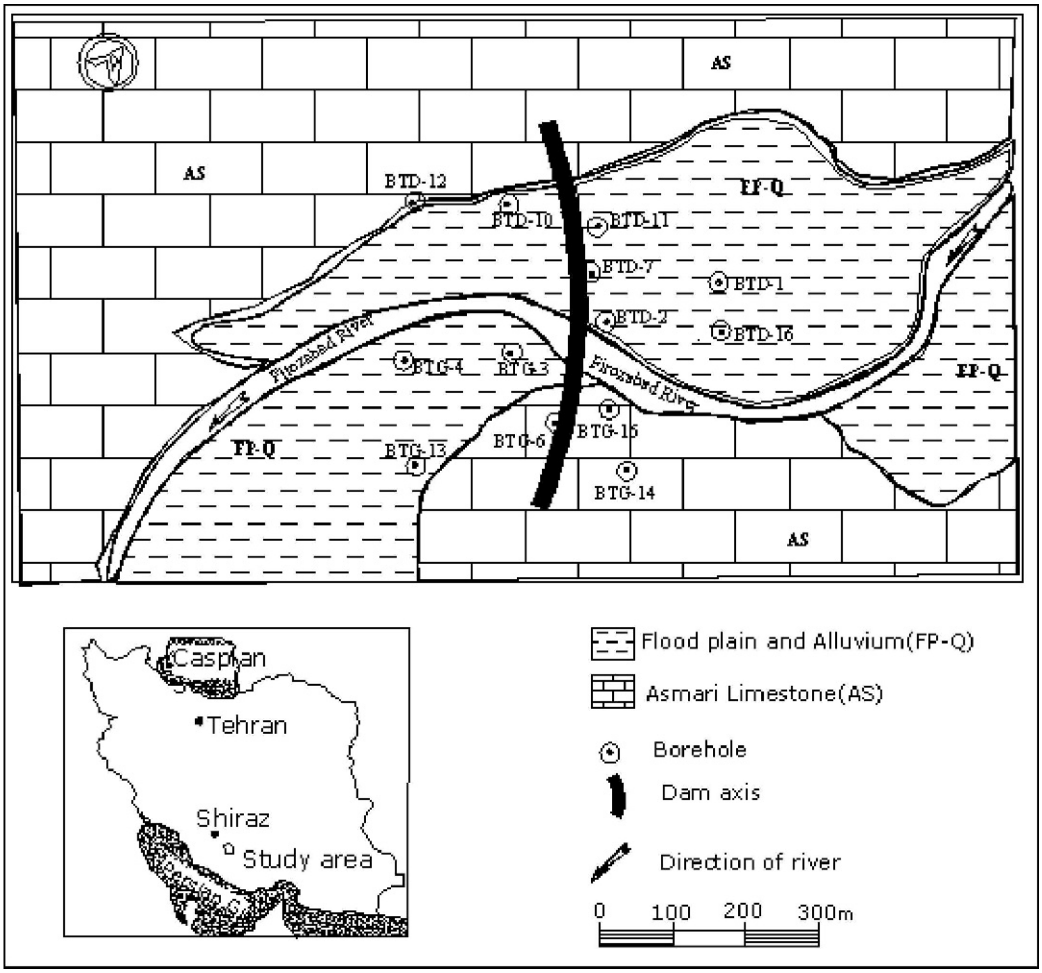

Figure 2. Location of the Tangab Dam and geologic map of the study area.

have formed along joints on the northern flank, 500 m and 100 m from the inlet of the valley. A 30 m deep shaft of 3 m diameter was discovered during tunnel excavation at the dam site. Injected dye tracers from boreholes of the right and left embankment were detected in the downstream springs.

The first dye tracing test was carried out by Asadi (1998) on the right bank. This study proved the hydrogeological connection between the dam site and the main springs of Tangab gorge. Evaluated average flow velocities are from 21 to 200 mh^{-1} (Asadi, 1998).

The second tracing test was executed by Talaie (1999). This test concludes that the main passage of water flow is from the reservoir through the left abutment of the dam site in the direction of the river. None of these studies reveal conduit flow from the right to the left bank of the dam, but there could be a conduit flow connection from the left bank of the dam to the springs downstream of the dam axis (Talaie, 1999). Therefore, despite a dominant diffuse-flow system close to the dam site based on boreholes and galleries observations, discovered caves and shaft and tracing tests results reveal the possibility of a conduit-flow system. The quantitative analysis of uncertainty associated with estimation of leakage is conducted for two simple one-dimensional flow conditions, including diffuse and conduit, in the following sections.

Diffuse Flow System

Assuming a one-dimensional diffuse-flow system, water leakage is estimated using the Darcy equation (Equation 1). Uncertainty associated with leakage is analyzed for two scenarios of dam construction: with and without any grout curtains. The input parameters in this analysis are permeability, hydraulic gradient, and cross-sectional area (k, i and A in Equation 1).

In the first scenario (construction of the dam without grout curtain), probable leakage is calculated using the Darcy equation by applying the DPD method to produce all cross combinations of permeability, hydraulic gradient and cross-sectional area. Permeability was measured in 13 boreholes (Fig. 2) by the Lugeon method. The Lugeon test was done during drilling operation in sections of 5 m in depth in all boreholes. A total of 261 Lugeon tests were performed in these boreholes. Permeability ranges from 1

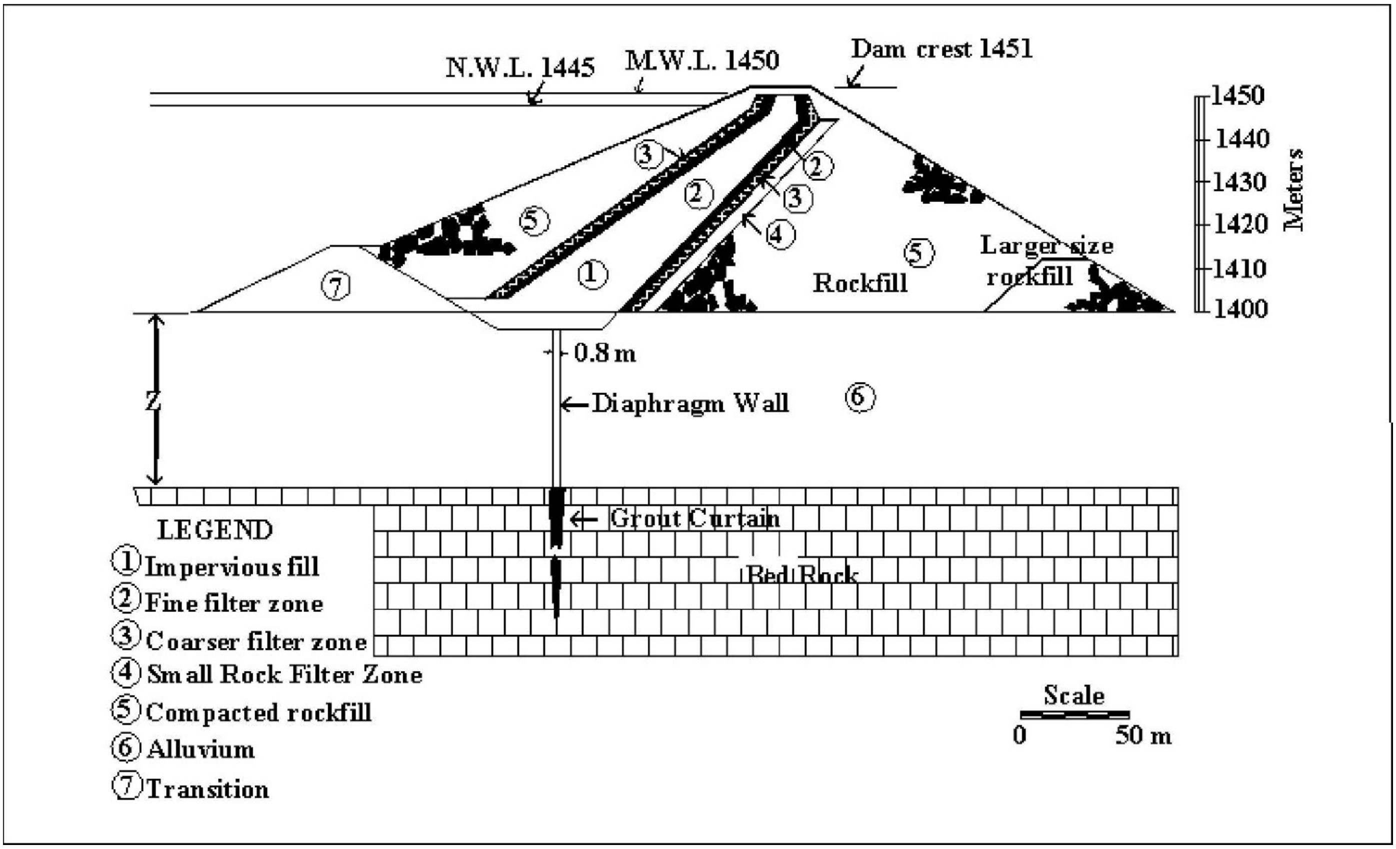

Figure 3. Typical cross section of the Tangab Dam and foundation.

to more than 100 Lugeon units. About 48% of permeability values are less than 5 Lugeon units and 17% are more than 50 Lugeon units.

Water levels were observed to range from 1370 to 1374 m above Mean Sea Level (MSL) close to the dam axis. The hydraulic gradient before construction at Tangab Dam site was around 0.001 using isopotential maps (Nadri, 1999). Both banks are recharged by the river based on the isopotential maps. After construction of Tangab Dam, normal water level at the reservoir will be 1445 m above MSL, and maximum water head difference between upstream and downstream from dam axis (at a distance about 110 m) will be about 75 m. Consequently, maximum hydraulic gradient will be about 0.6. Random data for hydraulic gradient were generated between the lower limit (0.001 before dam construction) and the upper limit (0.6 after dam construction without grout curtain).

The reservoir will be in contact with Asmari Limestone beyond the designed grout curtain (Fig. 4) at both abutments and depth. Assuming normal water level in

Table 1. Technical characteristics of the Tangab Dam.

Purpose	Flood Control and Irrigation
Type	Rock-fill embankment with clay core
Embankment volume	1.4 million m^3
Crest length	270 m
Crest width	10 m
Crest elevation	1452.5 m above MSL
Height from foundation	55 m
Height from river bed	51 m
Maximum water level	1451 m above MSL
Normal water level	1447 m above MSL
Reservoir volume at maximum water level	130 km^2
Reservoir volume at normal water level	10 km^2

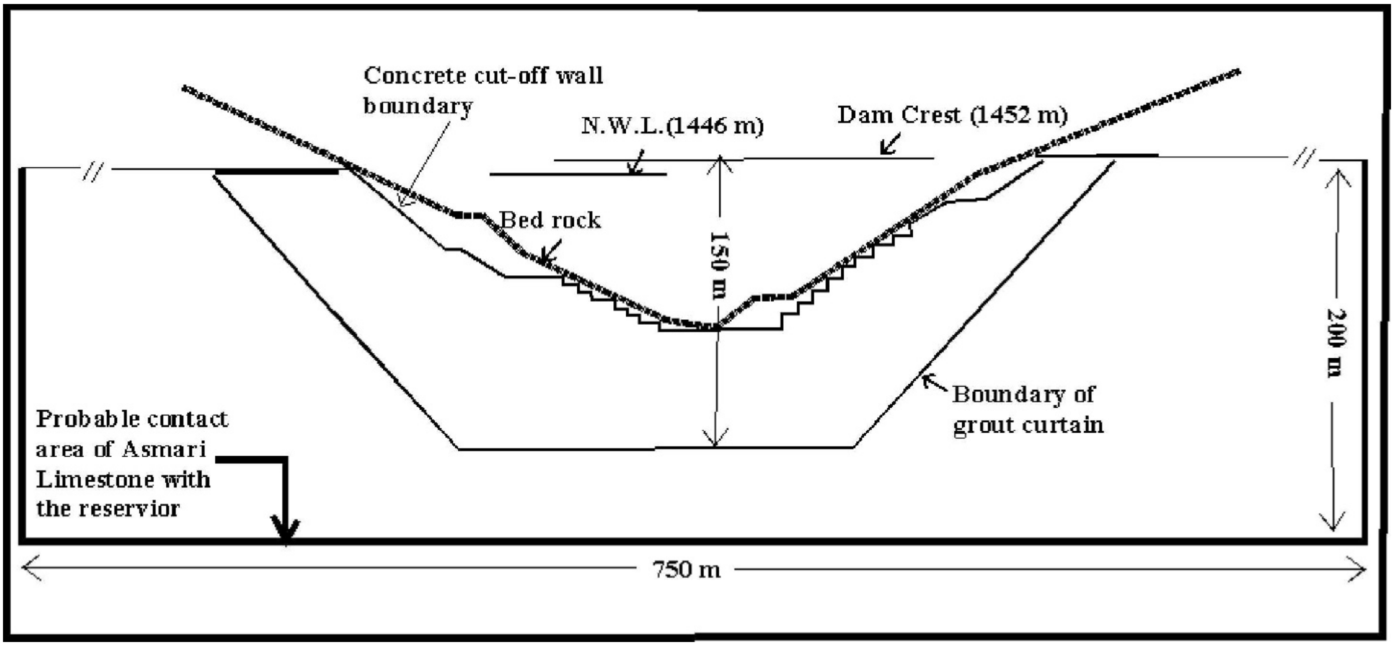

Figure 4. Dimension of grout curtain at the Tangab Dam and probable cross sectional area of leakage.

the reservoir, the probable cross section of leakage along the dam axis is estimated to be 750 m length (at both abutments) and 200 m depth according to outcrop of Asmari limestone at abutments of the dam site. The cross section area of the Tangab gorge (35 m high × 200 m wide) along the dam axis should be subtracted from this area (Fig. 4).

The probability distribution of estimated leakage is lognormal. Statistical parameters are presented in Table 2. The mean and maximum leakage rates are about 0.2 and 1.5 $m^3\ s^{-1}$, respectively. The maximum value of leakage was calculated using the maximum values of permeability and hydraulic gradient. The maximum permeability is 22 times more than the average, and 90% of the permeability data are less than the maximum value. Therefore, maximum leakage is not a true representation of the diffuse leakage flow. The mean leakage at 95% confidence interval (0.19 ± 0.05 $m^3\ s^{-1}$) can be considered as the most reliable leakage value.

The second scenario is the construction of the Tangab Dam with 270 m grout curtains in the right and left abutments (Fig. 4). Permeability data are identical to the first scenario. However after construction of the dam with designed grout curtain, the hydraulic gradient will be decreased to 0.1 because the length of leakage flow between upstream and downstream from the dam axis will be increased due to construction of the grout curtain. Therefore, hydraulic gradient ranges from 0.001 (before dam construction) to 0.1 (after construction of dam with grout curtain).

The probable cross sectional dimension of leakage is the assumed total contact area of the reservoir with the Asmari limestone at both abutments and depth minus the areas that will be blocked by construction of the grout curtain (Fig. 4). The statistical parameters of the uncertainty analysis are presented in Table 3.

The mean probable leakage is estimated equal to 0.2 ± 0.005 $m^3\ s^{-1}$. The mean probable leakage in the second

Table 2. Statistical parameters of leakage uncertainty without grout curtains at diffuse flow system (First strategy: $i = 0.001$–0.6).

Statistical Parameters	Permeability ($m\ s^{-1}$)	Hydraulic gradient (dimen.)	Probable leakage ($m^3\ s^{-1}$)
Minimum	1.70×10^{-7}	0.001	4.86×10^{-5}
Mean	4.10×10^{-6}	0.296	0.19
Maximum	8.90×10^{-5}	0.6	1.51
Variance	5.05×10^{-11}	0.044	0.51
Skewness	1.4	−0.054	2.51
Conf. Interval (95%)	1.00×10^{-6}	0.041	0.048
Coeff. of Variation	1.6	0.709	2

Table 3. Statistical parameters of leakage uncertainty with grout curtains at diffuse flow system (Second strategy: $i = 0.001$–0.6).

Statistical Parameters	Permeability (m s^{-1})	Hydraulic gradient (dimen.)	Probable leakage (m^3 s^{-1})
Minimum	1.70×10^{-7}	0.001	3.16×10^{-5}
Mean	4.10×10^{-6}	4.90×10^{-2}	0.02
Maximum	8.90×10^{-5}	0.01	0.16
Variance	5.05×10^{-11}	1.16×10^{-3}	1.74×10^{-3}
Skewness	1.46	0.02	2.54
Conf. Interval (95%)	1.00×10^{-6}	6.66×10^{-3}	5.17×10^{-3}
Coeff. of Variation	1.57	0.69	2.03

strategy reduces to less than 88% of the value estimated in the first strategy. This emphasizes the effectiveness of a grout curtain in a diffuse flow system. However, both strategies in diffuse flow system imply that the amount of leakage in the Tangab Dam site is not significant (less than 5% of mean annual discharge of Firozabad River), and that the dam may be constructed without the necessity of grout curtains, assuming diffuse flow.

Conduit Flow System

In spite of absence of solution cavities and major conduits in boreholes, two caves and shafts at the left embankment of the Tangab Dam, and the results of dye-tracing tests reveal that a conduit system exists at the study area. The probable leakage in a one-dimensional conduit flow system is estimated using the Darcy-Weisbach equation (Equation 2) for a single conduit in two scenarios of dam construction: with and without a grout curtain. The input parameters are hydraulic gradient, diameter of conduit, and friction factor (i, d, and f in Equation 2).

In the first scenario, hydraulic gradient ranges from 0.001 before, to 0.6 after, construction of the dam without a grout curtain. The lower limit of the conduit cross section is assumed to be the threshold of the turbulent flow, which occurs around the conduit having 0.5 cm diameter for commonly observed hydraulic gradient (White, 1988). The upper limit of the conduit cross section is very difficult to determine in a complex karst system. The cross section of the caves in the left abutment of the Tangab Dam ranges from a series of small openings in the end of the caves to more than 12 m^2. The smallest cross section along the flow path from inlet to outlet controls the leakage. The uncertainty is analyzed under four single upper limits of conduit diameters equal to 0.5, 1, 2, and 4 m. The lower and upper limits of friction factor are assumed to be 0.01 and 0.1 (Ford and Williams, 1989).

The probability distribution of generated random data of hydraulic gradient, friction factor and conduit diameter is evaluated to be normal (Table 4). The Darcy Weisbach equation (Equation 2) is used to calculate the probable leakage by means of DPD method for all the combinations of the input parameters.

The statistical parameters of the leakage probability distribution function in the first strategy are presented in Table 4. The mean of probable leakage at 95% confidence interval is about 0.8 ± 0.1, 4.67 ± 0.64, 19 ± 2.7 and 131 ± 17 m^3 s^{-1} for a single cross section with diameter of 0.5, 1, 2, and 4 m, respectively. All values of leakage are more than 10% of mean annual discharge of Firoozabad River.

Leakage is strongly dependent on the conduit cross sectional area. The leakage of a 4 m diameter conduit (cross section area of 12.5 m^2) is 163 times more than the leakage of 0.5 m diameter conduit (cross sectional area of 0.2 m^2) while the cross sectional area ratio is 60. This implies that the uncertainty increases with the increase of conduit dimension. It can be concluded that information regarding the dimension and number of major conduit systems can decrease leakage uncertainty.

In the second scenario (construction of dam with grout curtain), all the input parameters are identical to the first scenario except hydraulic gradient that ranges from 0.001 before to 0.1 after construction of dam, respectively. The statistical parameters of probable leakage are presented in Table 5. The mean probable leakage at 95% confidence interval is about 0.33 ± 0.04, 1.94 ± 0.25, 8 ± 1.1 and 54.6 ± 7 m^3 s^{-1} for a single cross section with diameter of 0.5, 1, 2, and 4 m, respectively.

The mean leakage decreases to less than 50% of the mean leakage obtained when the dam is constructed without grout curtains. The effectiveness of grout curtains depends on the lack of major conduits outside the grout curtain area. Detailed studies on stratigraphic and tectonic settings, karst hydrogeology, geomorphology, speleogenesis, and several dye tracings outside the proposed grout curtain area can determine the karst development and existence of possible conduits in this region, and help to reduce leakage uncertainty (Mohammadi et al., 2007).

CONCLUSIONS

Leakage from dam sites has been reported in numerous dams in karst areas. The estimation of leakage (i.e., location, path and quantity) can have errors due to uncertainties in the non-homogenous nature of a karst

Table 4. Statistical parameters of leakage uncertainty without grout curtains at conduit flow system (First strategy $i = 0.001$–0.6) for maximum conduit diameters of 0.5, 1, 2, and 4 m.

Statistical parameters	Hydraulic gradient	Friction factor	Conduit diameter alternatives				Probable leakage (m s^{-1})			
			D$_1$[a]	D$_2$[b]	D$_3$[c]	D$_4$[d]	D$_1$[a]	D$_2$[b]	D$_3$[c]	D$_4$[d]
Minimum	0.001	0.01	0.005	0.005	0.005	0.005	0.0045	0.0045	0.0045	0.0045
Mean	0.296	0.057	0.252	0.48	0.99	2.01	0.8	4.67	19	131
Maximum	0.6	0.1	0.5	1	2	4	3.04	16.7	74	472
Variance	0.044	7.9×10^{-4}	0.031	0.12	0.49	2.1	0.76	26.3	481	20,138
Skewness	−0.054	−0.07	−0.06	−0.09	−0.1	−0.3	1.2	0.6	0.9	1
Conf. Interval (95%)	0.041	5.5×10^{-3}	0.034	0.047	0.13	0.28	0.1	0.64	2.7	17
Coef. of Variation	0.709	0.49	0.6	0.69	0.8	0.9	1.1	1.9	2.4	3.2

[a] D$_1$ = Conduit diameter ranges from 0.005 to 0.5 m.
[b] D$_2$ = Conduit diameter ranges from 0.005 to 1.0 m.
[c] D$_3$ = Conduit diameter ranges from 0.005 to 2.0 m.
[d] D$_4$ = Conduit diameter ranges from 0.005 to 4.0 m.

formation and conventional methods of study (boring and geological mapping). An uncertainty analysis requires a significant amount of data as input. Data collection is expensive and time consuming, particularly in complex non-homogenous karst dam sites. Therefore, in the case of limited data, a qualitative uncertainty analysis can be applied.

All obtained information about karst development based on the measurements and tests in the boreholes may contain uncertainty. Karst development is a heterogeneous process making the detection of critical leakage zones difficult. Boreholes are representative of only a small fraction of karst-aquifer area, and the chances of missing large caves are high. The probability of a borehole tapping major conduits is also low, because the conduit systems occupy a low percentage of a karst aquifer. Therefore, the flow in a diffuse system is mainly indicated by water-table configuration (isopotential map), and conduit flow is not apparent. Dye tracing is a point-to-point process, and it is dependent on the location of the injection and sampling points. Therefore, major karst conduits may be missed. The dye may dilute significantly to the extent that it cannot be detected at the sampling points. Furthermore, karst conduits are small in size and they cannot be located precisely based on geological maps. Karst aquifers contain both diffuse and conduit flow regimes. It is a very difficult task to determine the percentage of diffuse and conduit flow and the cross section of the conduit. Therefore, great uncertainty is inherent in model selection.

In this study, quantitative uncertainty analysis was carried out on one-dimensional diffuse and conduit flow systems for two different strategies of construction of the

Table 5. Statistical parameters of leakage uncertainty without grout curtains at conduit flow system (Second strategy $i =$ 0.001–0.1) for maximum conduit diameters of 0.5, 1, 2, and 4 m.

Statistical Parameters	Hydraulic gradient	Friction factor	Conduit diameter alternatives				Probable leakage (m s^{-1})			
			D$_1$[a]	D$_2$[b]	D$_3$[c]	D$_4$[d]	D$_1$[a]	D$_2$[b]	D$_3$[c]	D$_4$[d]
Minimum	0.001	0.01	0.005	0.005	0.005	0.005	0.0044	0.0044	0.0044	0.0044
Mean	4.90×10^{-2}	0.057	0.252	0.48	0.99	2.01	0.33	1.94	8	54.6
Maximum	0.01	0.1	0.5	1	2	4	1.24	6.85	30.2	193
Variance	1.16×10^{-3}	7.9×10^{-4}	0.031	0.12	0.49	2.1	0.12	4.1	76.5	3184
Skewness	0.02	−0.07	−0.06	−0.09	−0.1	−0.03	1.2	1	1.3	1
Conf. Interval (95%)	6.66×10^{-3}	5.5×10^{-3}	0.034	0.047	0.13	0.28	0.04	0.25	1.1	6.9
Coef. of Variation	0.69	0.49	0.6	0.69	0.8	0.9	1	1.3	1.8	2.3

[a] D$_1$ = Conduit diameter ranges from 0.005 to 0.5 m.
[b] D$_2$ = Conduit diameter ranges from 0.005 to 1.0 m.
[c] D$_3$ = Conduit diameter ranges from 0.005 to 2.0 m.
[d] D$_4$ = Conduit diameter ranges from 0.005 to 4.0 m.

Tangab Dam, the Zagros region, Iran, with and without any grout curtains. The input parameters are the probability distribution function of the measured permeability, cross-sectional area (with and without grout curtain), generated data of hydraulic gradient (lower and upper limits correspond to before and after dam construction, respectively), conduit diameter (ranging upward from turbulent flow threshold and observed caves and shafts at the Tangab Dam site), and friction factor.

The mean of probable leakage in diffuse flow system is not significant (less than 10% of the mean annual discharge of river), with or without grout curtains. The mean probable leakage could reduce to less than 88% and 50% in a diffuse flow and conduit flow system, respectively, due to construction of a grout curtain. Leakage uncertainty arises mainly from the conduit flow especially outside the grout curtain area. Conduits might develop at the normal water surface. Leakage is significantly dependent on the conduit diameter. Determination of conduit flow outside the grout curtain is the most important approach for decreasing leakage uncertainty. An extensive and detailed investigation on stratigraphic and tectonic settings, karst hydrogeology, geomorphology, speologenesis, and several dye tracings outside the proposed grout curtain area may succeed in locating the possible conduits in this region, and thus reducing the leakage uncertainty.

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