Hydraulic behavior of rock masses around historical underground structures (Boleiti tunnel and Daryun canal) of Shushtar City, Iran

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ABSTRACT

Today, the key role of geotechnical investigations in the rehabilitation of hydraulic structures, especially structures with a historical background, is well known. Regarding to the multi-purpose importance of Shushtar Historical Hydraulic System, the role of geological factors in the hydraulic behavior of the rock masses around the two underground structures of the above-mentioned system, namely Boleiti tunnel and Daryun canal, based on geotechnical investigations carried out aimed at their maintenance is reviewed in this article. The system dating back to nearly 2000 years ago is consisted of 13 dams, water mills, waterfalls, water conveyance tunnels as an integrated hydraulic system, all of them were constructed over Karun River. The two studied structures were dug in Aghajari Sandstone Formation of Mio-Pliocene Age and suffered some damage due to various reasons. Although the tunnel walls of both structures are almost stable however, erosion of marly inter-layers at water contact and solution of clayey lenses within sandstone layers caused some collapses. The permeability of sandstones and marlstones were measured as 1 to 15 and 0 to 30 Lugeons, respectively with their durability indices of 77 and 36 percent on the average. It must be noted that seepage of sewerage system and heavy vehicles traffics amplified collapses. Finally, based on the geotechnical investigations and considering archaeological limitations, some treatments including rock fill retaining walls, timber trusses and very limited shotcrete lining have been done to stabilize the tunnels.
Keywords: Hydraulic behaviour, Geotechnical investigations, Shushtar City, Stability

INTRODUCTION

The hydraulic behavior of geological formations and rock masses is one of the key considerations in rock engineering applications for underground excavations. Most underground excavations encounter various direct and indirect groundwater challenges, which increase time, cost, and risk while reducing operational safety and efficiency. From an engineering geology perspective, a clear relationship exists between the engineering properties — particularly the hydraulic characteristics — of each rock unit and its geological attributes such as origin, composition, sedimentary and diagenetic history, alteration, and weathering (Barjasteh, 2003). Groundwater inflow into underground workings results from the interaction of regional hydrogeology, geological structure, and flow paths, and successful remediation requires a correct understanding of these relationships (Freeze & Cherry 1979). Given the historical, agricultural, and economic importance of the Shushtar Historical Hydraulic System (Edmonds, 2010; Kasravi, 1923). this paper investigates the influence of geological factors on the hydraulic behavior of the rock masses hosting the Boleiti Tunnel and the Daryun Canal based on geotechnical studies conducted for their rehabilitation. One of the fields of activity of Civil Engineering in particular,

Geotechnical Engineering is the maintenance of existing constructions and infrastructures; among these, the Cultural Heritage. The conservation of Heritage is one of the most challenging problems facing modern civilization. (Bilotta, et al., 2013).
The Shushtar Historical Hydraulic System (SHHS) demonstrates outstanding universal value as in its present form, it dates from the 3rd century CE, probably on older bases from the 5th century BCE. It is complete, with numerous functions, and large-scale, making it exceptional. The SHHS is a homogeneous hydraulic system, designed globally and completed in the 3rd century CE. It is as rich in its diversity of civil engineering structures and its constructions (Figure 1) as in the diversity of its uses (urban water supply, mills, irrigation, river transport, and defensive system). The SHHS testifies to the heritage and the synthesis of earlier Elamite and Mesopotamian knowhow. The Shushtar hydraulic system, in its ensemble and most particularly the Shadorvan Grand Weir (bridge-dam), has been considered a Wonder of the World not only by the Persians but also by the Arab-Muslims at the peak of their civilization. The Gargar canal is a veritable artificial watercourse which made possible the construction of a new town and the irrigation of a vast plain, at the time semi-desert. The Shushtar Historical Hydraulic System sits in an urban and rural landscape specific to the expression of its value.
Shushtar has long been one of the major centers of hydraulic engineering and multipurpose water structures before the Industrial Revolution. Researchers have described the integrated system of dams, bridges, canals, water mills, and river-based qanats as the Shushtar Historical Hydraulic System (SHHS). The complex includes 13 interconnected historical structures — dams, weirs, watermills, waterfalls, carved canals, and large water tunnels (Figure 1) — which function as a unified hydraulic system (Torfi, et al., 2020). The structures were built from the Achaemenid to Sassanid periods for optimal water utilization, incorporating advanced hydraulic knowledge long before the development of modern mathematical hydraulics (Barjasteh, 2003). This complex was inscribed as Iran's 10th UNESCO World Heritage Site on June 26, 2009 (No. 1315) (CHOS, 2023).

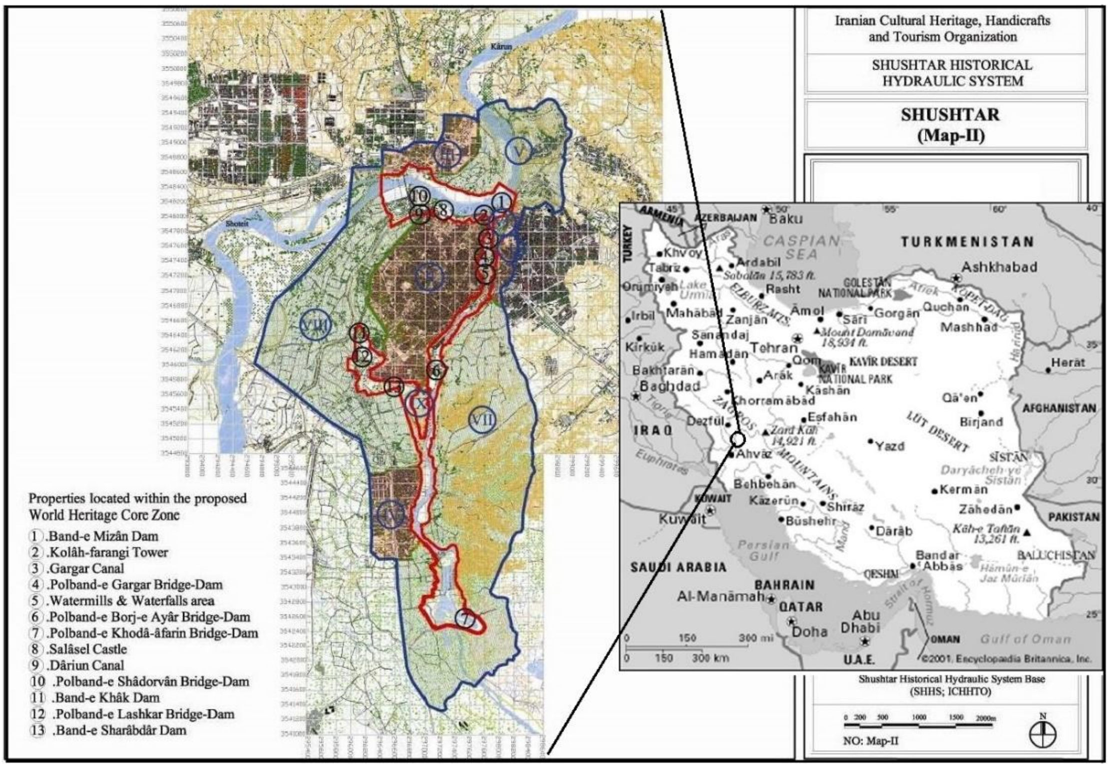

Figure 1. *Geographical location of Shushtar Historical Hydraulic System (CHOS, 2023).*

Over recent decades, several structures have suffered degradation and collapse due to factors such as urban wastewater leakage, overloading of nearby slopes, reduced flow in the Karun and the artificial Gargar tributary, and excessive upstream water extraction. Examples include:

* Western slope failures near the waterfalls and watermills due to leakage of urban wastewater, excessive loading, and construction of new buildings on unstable ground. After 1978 Revolution

proceeded by 1980 Iraq-Iran War, emigration of war impacted nearby cities or villages to Shushtar city increased its population suddenly without development of urban facilities including sewage network. Corruption and damage of the network and inadequate utilization and maintenance resulted in waste water seepage into Agha Jari Formation of the Gargar historical site. The waste water leaked from the marlstone- sandstone contact due to impermeability of the marly layers. The seeped and circulated waste water caused expansion and erosion of the marls which in turn caused continual slope failure and collapse.
* Collapse in the Boleiti Tunnel, which conveys water from the Gargar River to the waterfalls–watermills complex, exacerbated by reduced river discharge, decreased humidity, weakening of sandstone units, and construction activities above the tunnel. The Gargar River discharge is a function of the Karun River so that the average annual discharge of the former is about 10% of the latter downstream of the Karun1 dam (Hemadi and Jamei, 2006). After dam construction project on the Karun River Basin especially after impounding of Karun 1 (Abbaspour) in 1977, the water level of Karun River upstream of the Gargar dam-bridge decreased about 5 m so that the Boleiti tunnel which was usually submerged during wet seasons (winter and spring) was easily exposed to air circulation. The fluctuation of the water level caused weathering and erosion of marly layers and clayey lenses within the Agha Jari beds which in turn increased failure and instability of the tunnel walls.
* Collapse in the Daryun canal accompanied by sedimentation, which conveys water from the Karun River to the downstream Mian-Ab plain. The same waste water seepage into the Agha Jari beds as mentioned above for the Gargar site, happened here with lower rate due to more limited extent due to less population density.

Shushtar — founded after the establishment of the Achaemenid capital Shushan — is one of the oldest Iranian cities. The Karun River divides here into the Gargar (two-dangeh i.e., 2/6) (Figure 3) and Shoteit (four-dangeh i.e., 4/6) (Figure 4) branches. The Daryun watercourse is located on the Shoteit branch between the Mizan and Shadorvan weir-bridges, and its intake beneath the ancient Salasel Fortress includes two underground tunnels (CHOS, 2023; Torfi, et al., 2020; Barjasteh, 2003).
The width of Daryun canal is 2.2 to 4 m, and its height varies between 5 and 8 m. It is one of the most famous hydraulic structures on the Mian-Ab plain. Since the canal was dug during the Achaemenid period (529-330 B.C.), especially during the reign of Darius (521-485 B.C.), it carries the name Daryun. Flowing along the western side of Shushtar, this hand-dug stream irrigates its surrounding farming lands and forty thousand hectares of the Mian-Ab plain. After passing a course of 800 meters, the canal is divided into two branches at the dam of Band-e Khak (earth weir). Then, the first branch joins the Shoteit Canal at the dam of Band-e-Qir and the second branch joins the Gargar canal at the Lashkar dam-bridge.

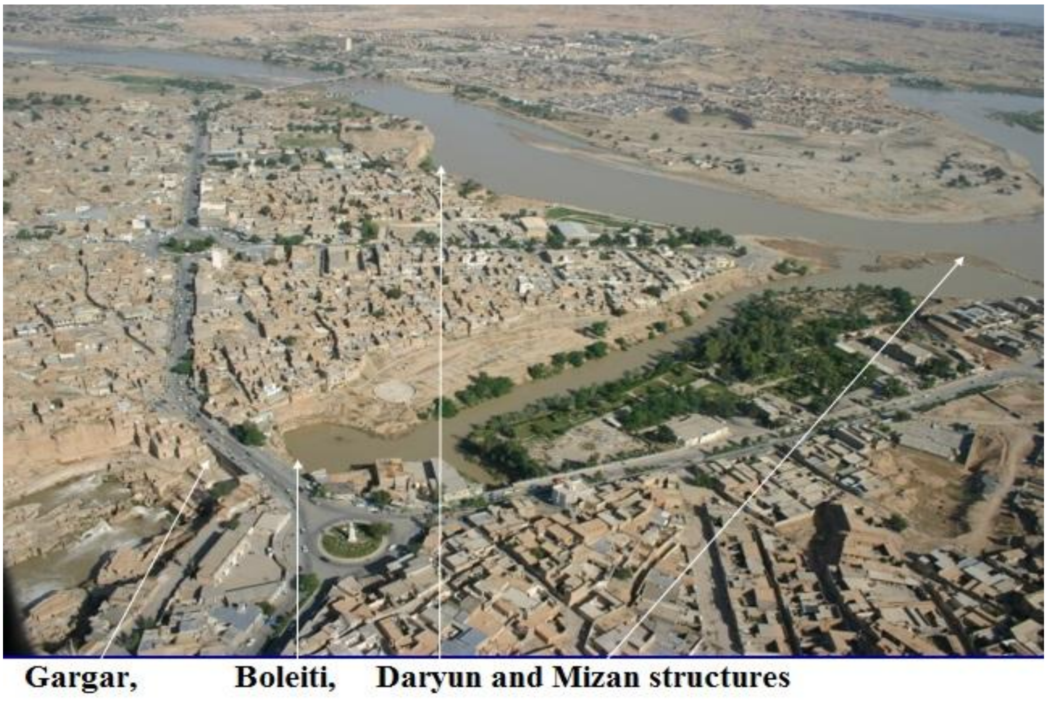

Figure 2. *Aerial view of the studied structures (NW view).*

The Gargar dam–bridge, located 400 m downstream of the Mizan weir, diverts water into three major tunnels (Shahr, Three-Furnaces, and Boleiti) carved into the Agha Jari Formation (Figure 2), supplying water to at least 32 watermills. These tunnels were excavated in fine-grained, weakly cemented sandstone with cross-bedding 3–5 m thick. The Boleiti Tunnel is approximately 354 m long, 4 m wide, and 8 m high, functioning historically as a flood-routing structure (CHOS, 2023; Torfi, et al., 2020; Barjasteh, 2003). Wastewater discharge, high-velocity flows, and closure of ventilation shafts caused damage and collapse along certain sections. Thin clayey inter-beds also occur within the sandstone sequence.

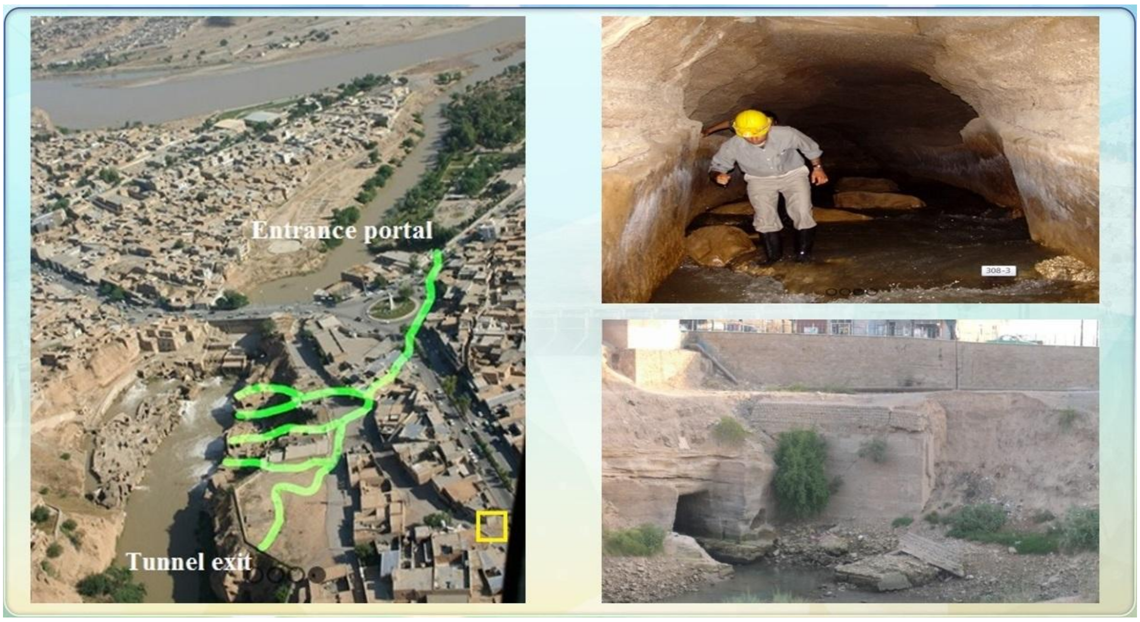

Figure 3. *Aerial view of the Boleiti tunnel (left) and its inlet portals (right). My paternal house in yellow.*

Figure 4. *Front view of Daryun canal before (left) and after (right) rehabilitation works (below).*

GEOLOGY OF THE UNDERGROUND STRUCTURES

The study area is part of the Dezful Embayment, located between the Zagros foothills and the Khuzestan plain (James & Wind, 1965). The main exposed formations are the Agha Jari Sandstone and the Bakhtiari Conglomerate (Barjasteh, 2003, 2015). Both the Boleiti Tunnel and the Daryun Canal were excavated within the Agha Jari Formation — an alternating sequence of sandstone, mudstone, gypsum, and marl (Abvarzan Co, 2005; SES, 2000). The sandstone contains poorly to moderately sorted, sub angular carbonate grains with weak calcareous cement (Figure 5). Sedimentary structures indicate fluvial deposition with channel (point-bar) sandstones and floodplain mudstones. Local conglomeratic lenses with clasts up to 5 cm suggest episodic high-energy flows. From a structural geology point of view, the formations lie on the southwestern limb of the Shushtar Anticline within the Dezful Embayment (Woodbridge, et al., 2015; Barjasteh, 2015). Its bedding dips 5° due southwest with two major vertical joint sets and one bedding-parallel joint set.

Figure 5. *Outcrop of Agha Jari Formation at Daryun canal (left) and Boleiti tunnel outlet (right).*

GEOTECHNICAL PROPERTIES OF THE HOST ROCK

Sandstone is one of the most abundant sedimentary rocks, comprising ~25% of all sedimentary units. Because of variations in composition and cementation, their physical and mechanical properties vary widely. Porosity, cement type, and grain fabric strongly influence strength (Taheri, et al., 2008). Seven 15-m boreholes were drilled along the Daryun alignment (SES, 2000). and five 25-m boreholes in the Boleiti Tunnel (Abvarzan Co, 2005). Most recently, a 25-m borehole was drilled upstream of Band –e Mizan weir-bridge (Figure 1) for river bank protection against flash floods. Geotechnical investigations identified three layers: alluvium, sandstone, and marl. The alluvial layer ranges from loose to very dense, with thicknesses of 1–7 m. The sandstone layer averages 5 m thick, underlain by marl extending to borehole depth. Durability index measurements yielded average values of 77% for sandstone and 36% for marl, indicating rapid weathering of marl upon exposure. All samples have a specific gravity of ~2.5 g/cm³; sandstone exhibits 1% water absorption consistent with its porosity, while clayey units show negligible absorption. A brief description of the data is given in tables 1 and 2.

Table 1. *Geomechanical properties of Agha Jari Formation at the studied sites (Abvarzan Co, 2005; SES, 2000).*

Name	Formation (Agha Jari)		
	Symbol	Unit	Value
Elastic modulus	E_i	GPa	7.25
Uniaxial Compressive Strength	UCS	MPa	62.39
Rock Quality Designation	RQD		47.25
Poisson’s ratio			0.3
Density	ρ	gr/cm²	2.54

Table 2. *Average geomechanical properties of Agha Jari Formation at the northwest part of Zagros region (Taheri, et al., 2008).*

Title	*Rock type*	*USC (MPa)*	*E (GPa)*
NW Zagros	Sandstone	21.64	2.85
	Siltstone	14.17	1.74
	Claystone	17.24	1.90

HYDRAULIC BEHAVIOR OF THE HOST ROCK MASS

Hydraulic behavior of geological formations and rock masses is one of the most important aspects of rock engineering application in underground excavations. Most underground excavations face direct and indirect groundwater challenges that increase time, cost, and risk, and reduce the safety and efficiency of operations. From the perspective of geotechnical engineering, there is a clear link between the engineering properties, especially the hydraulic properties of each rock layer, and its geological conditions such as origin, composition, sedimentary history, and weathering. Water seepage into underground excavations is a consequence of the interaction of regional hydrogeology, geological structure, and flow paths, and successful remediation of these problems requires a proper understanding of this relationship. Sandstone layers, depending on their lithological characteristics and the extent of their fracture system, can form aquifers with medium to low permeability that are mostly located among clay and marl units (Taheri, et al., 2008). On the other hand, the presence of these rock units can create perched aquifers in sandstone units that can locally cause leakage to other layers and into the tunnel. Clay and marl layers can act as aquitard and confining layers. Geotechnical results (Abvarzan Co, 2005; SES, 2000) confirm three layers: alluvium, sandstone, and marl. Clay layers show low permeability (0–3 Lugeons), while sandstone has slightly higher values (1–15 Lugeons). Sandstone layers act as natural subsurface drains, while underlying marl acts as an impermeable barrier directing groundwater flow along bedding. Impeded drainage leads to pore-pressure buildup, causing instability in the Daryun and Boleiti structures. Maximum swelling pressure of the marl is 1 kg/cm² with swelling up to 90%. Although sandstone generally has higher initial permeability, calcite cementation reduces flow, except where fracture networks create secondary permeability. Dissolution features and clay inter-beds locally increase porosity. Erosion around clay lenses further reduces stability. The impermeability of these layers caused an increase in pore pressure and instability in the roof and walls of the underground structures. Sandstone layers with higher initial permeability have higher cementation due to the crystallization of carbonate cement, although they sometimes form porous structures. The presence of a fracture system can increase secondary permeability in sandstone units. On the other hand, the fineness of the materials filling the joints of the rock, as well as the existing cement, will prevent increased permeability even if the cementation is weak.

Hydraulic mechanisms expected to rock instability are:

*Seepage through rock matrix (low in fine-grained marls and higher in sandstones).
* Flow through discontinuities- joints and bedding planes.
* Tunnel/canal inflow and blowouts where local gradients cause concentrated inflows or erosion of infillings.
* Pressure at the tunnels crown under high heads.
* Seasonal changes- dam operations or flood events produce transient responses.

CONCLUSIONS

Because the rehabilitation of the Daryun Canal and the Boleiti Tunnel aimed to restore water flow, assessing the stability of sidewalls—particularly following excavation and dredging—was essential. Geological and geotechnical characteristics of the host rock have created perched aquifers within sandstone layers. Their seepage into underlying clayey and marly interbeds leads to swelling, deformation, and collapse. Wet–dry cycles promote clay expansion, generating pressure on tunnel roofs and walls. Low rock strength further exacerbates failure. Fortunately, no significant collapses occurred during the restoration works.

Figure 6. *A view of Boleiti tunnel before (left) and after (right) rehabilitation works.*

Main causes of instability:

* Blockage of vertical shafts and increased saturation within sandstone layers,

* Loss of cementation in sandstone due to moisture increase,

* Erosion of clay cement between sandstone layers, leading to weakening and collapse.

REFERENCES

Abvarzan Consulting Engineers Co. (2005). Restoration of Boleiti channels and the estimates of channel volume. Technical report (in Persian), 65p.

Barjasteh, A. (2003).Geotechnical investigations for the rehabilitation of historic hydraulic structures around Shushtar City, Iran. Proc. Int. Conf. Construction of historical cities and geotechnical engineering. Saint Petersburg, Russia. 4p.

Barjasteh, A. (2012). Vulnerability of historic hydraulic structures of Shushtar City from a geotechnical earthquake engineering viewpoint. 15th World Conference on Earthquake Engineering (15WCEE). 24-28 Sept. Lisbon, Portugal. 9p.

Bilotta, E., Flora, A., Lirer, S., & Viggiani, C. (Editors) (2013). Geotechnics and Heritage. Taylor & Francis Group, London, UK. 273p.

Cultural Heritage Organization of Shushtar (CHOS) (2023). http:// www.shushtarch tb.ir. Accessed 20 Sept. 2023.

Edmonds, C. (2010). East and West of Zagros, Travel, War and Politics in Persia and Iraq 1913–1921. Brill, 377 p.

Freeze, R . A . , & Cherry , J . A. (1979). Groundwater. Prentice Hall, 604 pp.

Hemadi, K and Jamei, M. (2006). The role of Mizan and Gargar ancient structures on the regulation and control of the Gargar River flow and floods (in Persian). 1st Conference on Optimum Utilization of Water Resources, 5 Sept. Shahrekord University, Shahrekord, Iran. 5p.

James, G. A. & J. G. Wynd, J.G. (1965). Stratigraphic nomenclature of Iranian oil consortium agreement area: AAPG Bulletin, 49 (12): 2182-2245.

Kasravi, A. (1923). 500 years of Khuzestan history. Donyai Ketab Publisher (in Persian).426p.

SES Consulting Engineers Co. (2000). Geotechnical report of Daryun tunnel (in Persian). 77pp.

Taheri, D., Ghazvinian, A., Nikudel, M.R., & Khamehchian, M. (2008). Geomechanical evaluation of sedimentary rocks units of Aghajari formation in Zagros zone," Scientific Quarterly Journal of Iranian Association of Engineering Geology, 1 2 , p. 15-30.

Torfi, K., Albaji, M., Naseri, A.A., & Boroomand Nasab, S. (2020). An Introduction to the Ancient Irrigation Structures Upon Karun River in Shushtar City, Iran. Iranian Journal of Science and Technology, Transactions of Civil Engineering https://doi.org/10.1007/s40996-020-00490-x.

Woodbridge, K.P., Parsons, D.R., Heyvaert, V.M.A., Walstra, J., & Frostick, L.E. (2015). Characteristics of direct human impacts on the rivers Karun and Dez in lowland southwest Iran and their interactions with earth surface movements, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.10.088.