ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Historical Building Rehabilitation

2021-2022

Effects of drought on historical bridges. The case of Khaju Bridge on Zayayanderood River in Isfahan, Iran

Candidate: Mana Hejazi

Supervisor: Dr. Ernesto Antonin

(Fundamentals of Performance Design)

Co-Supervisor: Dr. Michela Marchi

Table of Contents

1. Introduction

The city of Isfahan is internationally recognized for its historic monuments belonging to different centuries. The oldest monuments in the city date back to the Sassanid period (224-651 AD) proving the very early origin of the city. Isfahan is also located on the banks of the Zayanderood river which flows through the city and shapes a part of its landscape. The river has been experiencing complete drought periods. This phenomenon has been taking place since 2000, when the diversion of its water started from the nearby province of Yazd, which was not included within the hydraulic basin of the river. Since then, the river is facing periods of complete drought reaching sometimes one year or even more. Although the causes of this phenomenon are categorized both as human-based and nature-based, the human-based ones emerge as crucial. A recent report (“What is the Reason of Drought of Zayanderood river”, 2021) also highlights that increasing the agricultural activities will worsen the situation and result in decrease of groundwater level (up to 150-200 m depth in some areas), which surely affects the subsidence in the whole area.

a b

Figure 1-1: a) Khaju Bridge with the presence of the flow of the river. (Source: Flickr.com), b) Khaju bridge in the absence of the flow of the river. (Photographer: Adam Jones, Source: Flickr)

It is also important to mention that climate change has reduced rainfall and that this has contributed to changing the river regime and directly affecting the stability of bridges whose foundation is located inside the riverbeds.

Usually, the physical phenomena affecting the buildings -especially the historic ones- are defined "natural hazards", but we should notice that those that are commonly defined in this way are: earthquake, wind, and snow, while the problem of drought on buildings has not been discussed as much as the others. Moreover, the problem becomes more important in the areas where historic bridges are present, as the river drought can damage not only their functional features of transport infrastructure, but also the historical values they embody, especially for the bridges which are classified as cultural heritage.

According to the local reports and media as well as the studies done on this area, the city of Isfahan is experiencing subsidence over a wide area, not only next to the river basin, but also in areas further from the riverbank. The cracks observed in historic buildings connected to the land subsidence has attracted the attention of people and activists in the field of cultural heritage buildings as well.

As it will be better explained below, the problem of the lack of water has been mentioned in some studies as a problem of bad water management This allows to argue that there are possibilities to slow down the phenomenon of drought, therefore by acting on the primary causes of the bridge decay, in parallel with its restoration.

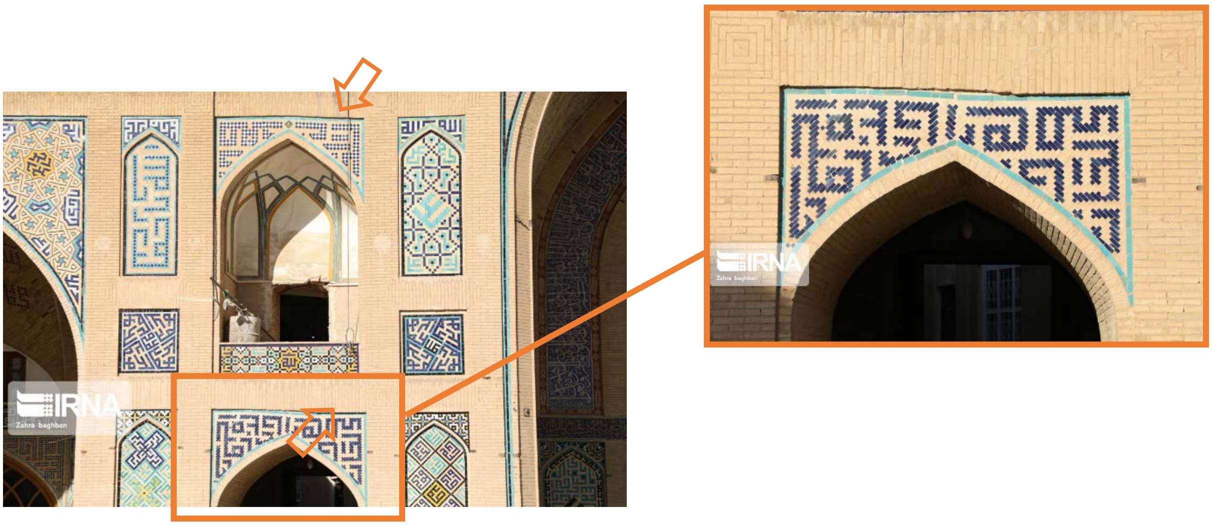


Figure 1-2: Some damages that are seen on the Khaju bridge (Photographer: Zahra Bagheban)

Concerning the river basin water regime, a study done in 2007-2008 by Ghasemi (Ghasemi, 2014) shows that almost 470,000,000 m^3 of water flowing from Zayanderood dam are lost, in addition to that legally diverted to agriculture, industry and urban uses (Table 1). This is mainly due to illegal water withdrawal that is suspected to take place in the upper course of the river, especially in Chahar-Mahal-Bakhtiari province, triggered by unemployment issues that push people to do informal agricultural works in these areas.

It has been confirmed that the drought periods have been intensified since 2000, due to the water supply to nearby provinces, power plants and refineries, while the irregular water harvesting in upstream section of the river, by both agriculture and big industries, have further worsened the situation. It has also been observed that the output and input of water in this area is not in balance, as each province through which this river passes decided and acts separately, taking decisions not based on significant studies and scientific data, which seriously affect the water regime of the river.

Table 1-1: Total output from Zayande-Rud and allocation of water to different parts (Ghasemi, 2014)

Purpose	Quantity (m^3)
Total Output	1,350,000,000
Agriculture	350,000,000
Industry	120,000,000
Urban Use	370,000,000- 400,000,000

The studies carried out on the river will be reviewed in detail in the following chapters, even with differences in methods and specific topics addressed. In general, their results agree in affirming that the practices adopted in water management have strongly and negatively affected the river system. This means that solutions to slow down or even stop this human-caused process can be found with a thoroguh investigation of the situation in a critical way.

Land subsidence is the main result of this imbalance in water use. This dynamic is affecting a wider area than the vicinities of the river, to the extent that local subsidence in parts of Isfahan has increased and accelerated in recent years, making it easy to observe cracks in many buildings as an effect of this phenomenon.

Sorkhabi et al. (Sorkhbi et al., 2022) estimated the subsidence rate in the area of Isfahan with InSAR, documenting that the maximum subsidence reaches 170 mm/year, while the average rate accounts for 110 mm/year. Although the cracks that appear in many buildings - especially in the historic ones- can have different causes and be interpreted variously, the study stated that land subsidence definitely affects the buildings of the city.

Although subsidence emerges as an important cause to be considered, and drought has also many economic, environmental, social, and even political aspects, the studies that have investigated the effects of drought on buildings in Isfahan are few and unsystematic, and even fewer are those dedicated to historical heritage.

This research field would need a multidisciplinary approach involving and combining several approaches and prespective since it should consider the many different and interconnected aspects of the problem.

This is true also for the present study, which has tried to observe the drought effects on the historic Khaju bridge of Isfahan considering different aspects involved in the phenomenon.

The research has been carried out beginning from a literature review on the topic of drought effects on historical buildings. This needed a collection and critical reflection an a vast set of sources, in order to set out what were the knowledge gap in the previous studies on the issue. One of the main limits that has to be acknowledged is that the impossibility to conduct the study directly in Iran, greatly complicated the acquisition of data and made any fieldtrip impossible. At the same time, it is known by the author that the current political situation in Iran usually impedes access to many useful documents that are held in local public offices and archives. Thus, the statistics and data that this study mentions are mostly gained by already published reports and previous studies, even if it would have been interesting to access more resources (even those kept away from the public) in order to analyze more data.

The research has been carried out in two steps, as explained below. A specific chapter is devoted to each of them in the following pages.

After introducing the history of the city of Isfahan and the role of the river over the shape of the city and its formation, the main issue related to the drought phenomenon is presented, highlighting its contemporary significance and current effects at the scale of the entire city of Isfahan. What this study pays particular attention to is the social related issues that might also derive from drought and water scarcity.

In chapter 4 is presented a technical analysis of the case study and its structure as well as the geotechnical situation of the building, in order to identify the present damages and possible dangers. In this chapter are also presented several techniques for monitoring and a selection of studies that also offer possible solutions for the structural problems related to subsidence. This provides a basis for critical analysis and for further studies on the issue fostering new possible ways to address the problem.

In chapter 5 is discussed the social related problematics not only in relation to the Khaju bridge, but in general, considering the effects for all historical bridges of Isfahan that should be considered as a system rather than single monuments.

The analysis of the current situation shows that the problem is severe and endangers the stability of the buildings in the area, as well as the social ways in which the bridges were traditionally used as physical connectors, but also public and social places for the citizens. Nevertheless, there is still hope to slow down the process and damages if immediate action is taken, at both local and wider scale. This study aims at providing a first overview on the topic in order to stimulate further and deeper investigations for the future. A better knowledge of the phenomena will allow to select the most effective actions in reviving the water system and regaining control of the structural stability of the structures as well as the revitalization of the social life connected to the bridges.

2. Context and background

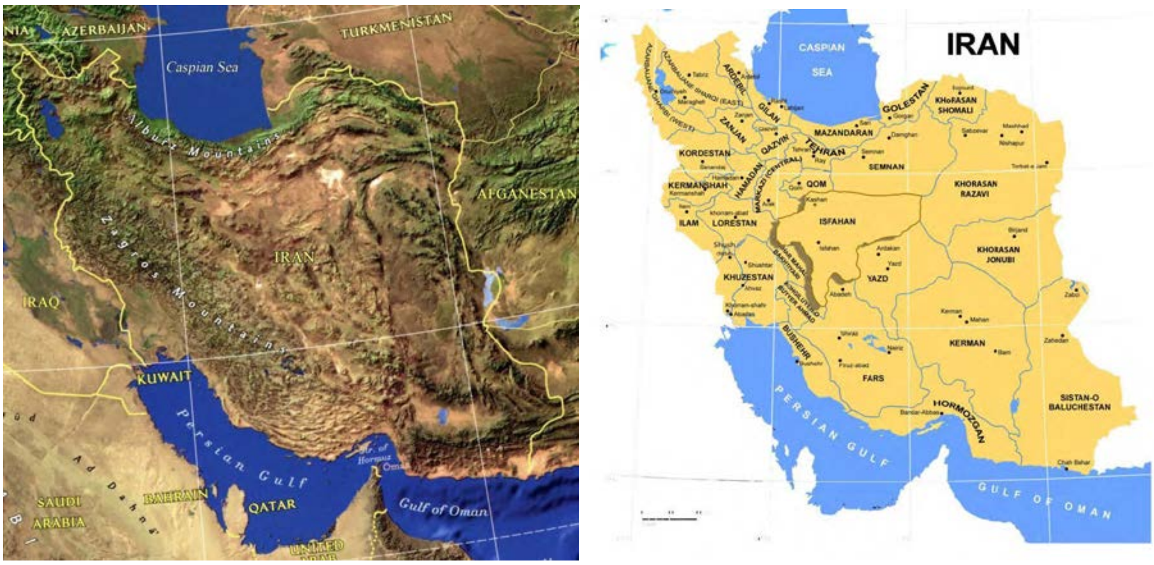
2.1. The City of Isfahan

The city of Isfahan (Lat: 32.661343; Long: 51.680374) is the capital city of the Isfahan Province, with an area of 105,937 km^2 and it is situated in the central part of Iran. After Mashhad and Tehran, Isfahan is the third largest city of the country, covering an area of 215 km^2. Since it hosts important industrial activities, the city has attracted a high number of immigrants, which increased the population to approximately 2,220,000 (in 2022) and also made it the second most polluted city of Iran.

The geographical situation of the province, placed in the middle of the Iranian plateau, includes both mountainous and lowland areas. This results in a variety of climatic conditions, spanning three categories: desert, semi-desert and cold semi-humid, while the climate of the city of Isfahan itself is classified as semi-desert. (Kazemi 2006, 35-39)

A dynamic urban settlement elongated on the sides of Zayandeh-Rud is documented since before the Safavid Period (XVI to XVIII century B.C.E.) in the historic parts of today's town.

Being the crossroad of north-south and east-west trade routes in central Asia as well, Isfahan became the splendid capital of Seljuqs (X to XII century B.C.E.) and Safavids, and it was well-known for its beauty from which derives the expression: "Isfahan, half of the world".



(a) (b)

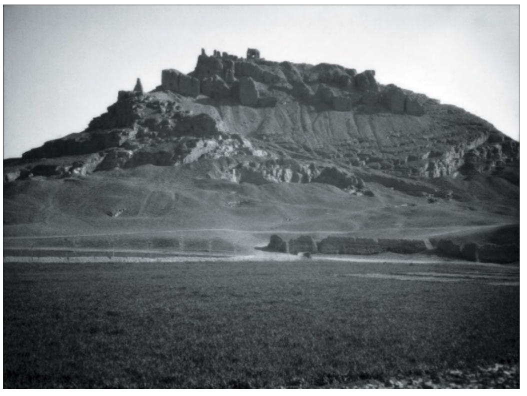
Figure 2-1: (a): Map of Iran , (b): Location of Isfahan Province

The river, which has historically been purposed for farm irrigation and supplying of drinkable water, is a characteristic element of city landscape, a beautiful scenery for the palaces constructed along the river, and also the site for various ceremonies. The construction of bridges has enhanced the connection between the riverbanks and enriched the social movements and activities of the inhabitants. Five historic bridges cross the Zayanderood river, 4 of them built in the Safavid period (even if in different times) (Hashemidehghani, 2019) and one (Shahrestan bridge) that was constructed in the Sassanid period.

2.2. History of Isfahan

The origin of Isfahan dates back to Sassanid Period and therefore the history of the area can be divided into two main stages, before and after the conquest of the Arabs, which in most of the studies are mentioned as pre-Islamic, and Islamic era[1]. The second part is divided into seven periods: an early Islamic period up to the 4th century A.H, then the Buyid dynasty, the Mongol era, the Safavid period, the Qajar period, the Pahlavi period and finally the current era (Ashrafi et al. 2020).

(a)



(b)

Figure 2-2: Shahrestan Bridge (Ashrafi et al. 2020), (b): Atashgah Isfahan (negarestandoc.ir)

2.2.1. Pre-Islamic Period and Early Islamic Period

The history of Isfahan from pre-historic period until the Sassanid dynasty is not clear and not thorough. There are evidences in the city such as Sassanid column capitals and also two monuments which prove the presence of this civilisation, for example: the Fire temple (also known as Atashgah) and Shahrestan Bridge, although these singular monuments are

[1] The latter ways to define these two periods are criticized by some, but there was not enough space to discuss this matter further in this work.

insufficient to reconstruct the history of the city at that itme. The name of Isfahan dates back to the Parthian period (247 B.C.E. to 224 C.E.).

In the early Islamic period, Isfahan was divided into two main areas: Jay, which was located near the river, and Yahudieh, located around 3 to 4Km away from the river. It is believed that after the invasion of the Arabs, the Yahudieh part developed gradually and resulted in what is nowadays the city of Isfahan. In the meanwhile, Jay had become a military zone during the invasion of the Arabs and was surrounded by defensive walls. Form the Arab invasions until the 4th century the social and political improvements resulted in the enlargement of the city and the spread of connecting systems surrounding to its centre.

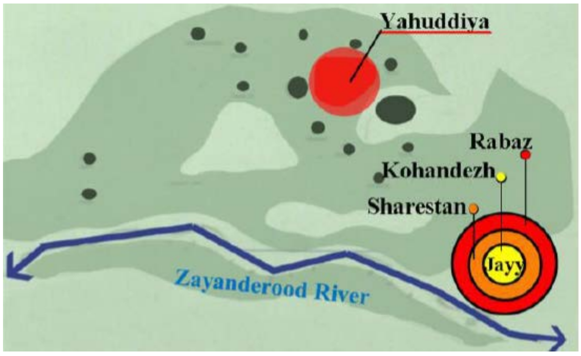


Figure 2-3: Jay and Yahudieh location (Ashrafi et al. 2020)

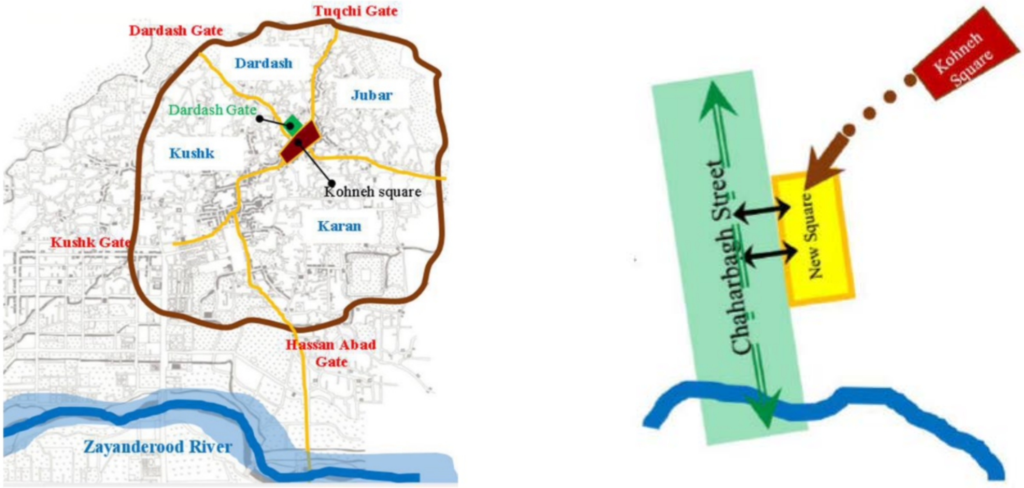
2.2.2. Buyid, Ghaznavid, Siljuq and Ilkhanate Period

In the Buyid era (934 to 1063 C.E.) Isfahan was chosen as the capital and the construction of a wall around the city was ordered, the remains of which existed until recently.

In the following Ghaznavid period, Isfahan did not expand a lot, while in the Seljuq era (mid-10th to the end of the 12th century) the city was chosen as the capital and important new palaces and different architectures were built, for example the central Kohne square (a quadrilateral space of three hundred steps long and one hundred steps wide, full of workshops). All the important parts the city were enclosed within the walls.

Isfahan was attacked during the Mongol invasions (mid-13th century), severely damaged and rebuilt in the Ilkhanate period (late 13th to mid-14th century).

Isfahan became the capital city again during the Safavid period (1598 C.E.), and a new seires of architectures were built, mostly replacing those of the previous periods. Naqsheh Jahan square, Chahar-Baq-Abbasi boulevard and Shah-Abbas Mosque are among the most important interventions of this period. It was in the Safavid period that a new expansion was decided toward the Zayandeh-Rud, in the southern part of the city, and four bridges across the river were built.



(a) (b)

Figure 2-4: (a) Buyid Fence (Ashrafi et al. 2020), (b) The urban expantion in Safavid period

2.2.3. Afshar, Zandiye and Qajar Period

No architecture has been found belonging to the Afshar and Zandiye era, which followed the Safavid period and preceded the Qajar period (late 18th to early 20th century), during which the once glorious places of the Safavid era continued to remain deserted. The only important work belonging to this period is Chahar-Bagh-khajuo as an imitation of the Safavid Chahar-Baq-Abbasi.

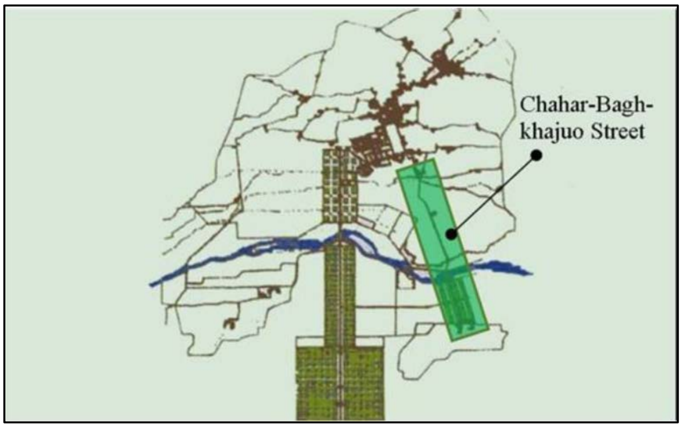


Figure 2-5: Urban mapping in Qajar period

2.2.4. Pahlavi and Islamic Revolution Period

The historic urban fabric was strongly manipulated in the Pahlavi period (1925 to 1975), featuring an overwhelming introduction of modernist building such as many governmental and administrative architectures that were placed all over the city. This has altered the organic fabric of the city, as the urban layout became more and more heterogeneous following the implementation of large projects like new roads that were desinged without basing them on careful and sensitive studies. The same approach was continued even after the Islamic revolution (1979) and the 8 years of Iran-Iraq war. In this time, urban growth was still conducted with little consideration and based on no studies as well as control and supervision, therefore having an impact on the opportunities for a balanced organization of the city. In fact, the massive immigration to the cities and the war intensified these trends, those that were initiated in the second Pahlavi's era.

2.3. The Climatic Condition of Isfahan

To identify the climatic situation of Isfahan, the Köppen classification has been used here. The Köppen classification is the most used climatic classification established by Wladimir Köppen, first published in 1884, and since then it underwent several modifications, till the latest which was done by the German climatologist Rudolf Geiger (1894-1981), thus its current name: Köppen- Geiger climate classification system. This system consists of five main groups of climate conditions, each with subgroups, established according to precipitation and temperature patterns, which are expressed by a code of three letters. Based on this classification, the climatic condition of Isfahan is categorized under BSk, which refers to a Tropical and Subtropical Steppe Climate.

Table 2-1: Summary of Isfahan climatic condition (Source:Weatherbase.com)

Description	Quantity
Average Temperature	16.7 °C
Warmest month on average and the average temperature	July, 29.4 °C
Coolest month on average and average temperature	January, 2.2 °C
Highest recorded temperature	40 °C
Lowest recorded temperature	-11.1 °C
Average amount of precipitation	114.3 mm
The month with most precipitation on average	January, 17.8 mm
The month with the least precipitation on average	June, 0 mm

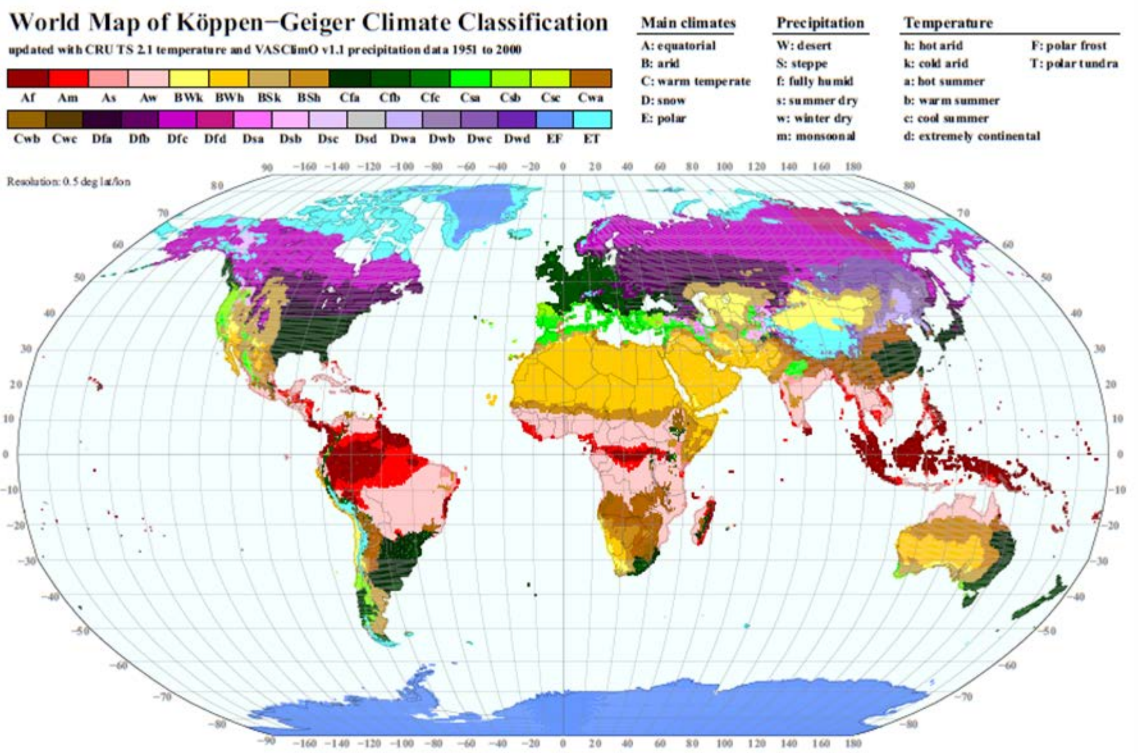
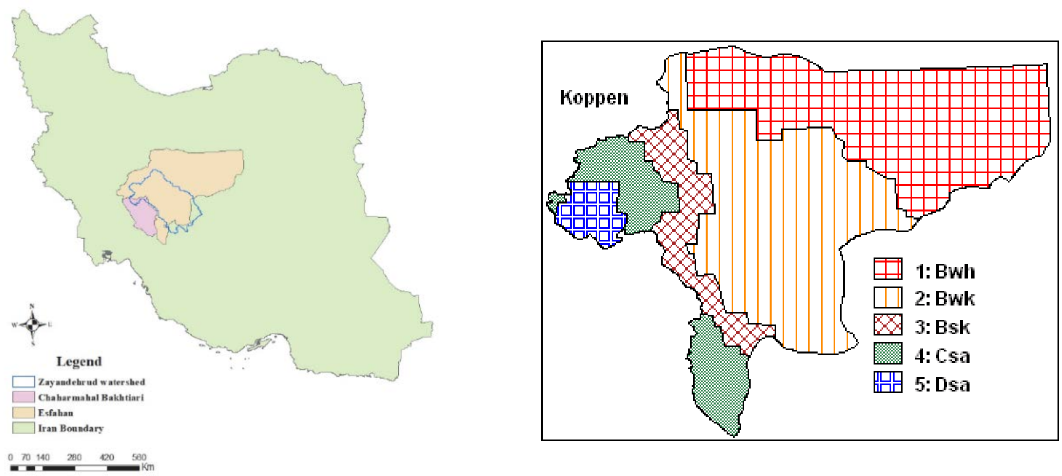


Figure 2-6: World map of Köppen- Geiger Climate Classification (Source:Weatherbase.com)

Since the irrigation basin of Zayanderood does not include Isfahan only, it is also important to have a look on the more detailed climatic classification of the area. As shown in Figure 2-7, most of the basin includes lands being classified as arid.



a b

Figure 2-7: (a) Location of Isfahan and Chaharmahal Bakhtiari Provinces with the presence of Zayanderood Irrigation Basin (Blue Line). (b) Climatic Classification of Isfahan Province using Köppen (Yaghmaei et al., 2009)

The precipitation rate in Isfahan province varies year by year and increases moving from east to west: the average rainfall is from 100 mm per year in the east, to nearly 450 mm per year in the west parts. Rains occur mostly in cold seasons, while the evaporation rate is 2500 mm per year. The area is subject to desertification, mostly due to water resource depletion, population pressure, excessive grazing, wrong water management practices and climatic factors (Jafari, 2016).

Moreover, based on a study by Hosseini Abri (Hosseini Abri, 2003) considering that Isfahan is surrounded on 3 sides by the desert (east, north, south) and the west side is also classified as a desert area (average rainfall of 125 mm and evaporation of 3000 mm over 50 years), the city has to be classified as a desert city. Throughout history, nearly 18% of the river's water flow has been allocated to the city of Isfahan, whose canal network assured its correct distribution, since the drought period did not exceed 11 days every 18. It should be mentioned that although the periods of drought have been historically recurrent, the city of Isfahan never suffered from being negated access to the river water as it is currently happening. I general, according to the documents written by Sheikh Bahaei, a portion of 6/33 of the water of Zayanderood was commonly allocated to the city of Isfahan.

2.4. Zayanderood river and its impact on the formation of the City

Zayanderood is the longest river in middle Iranian Plateau. The river springs from the Zagros Mountain range, southwest of the city of Isfahan, flows across the Isfahan plain irrigating it, and finally ends in Gavkhuni marsh, located 140 km south-east of the City. (Kazemi 2006, 35-39)

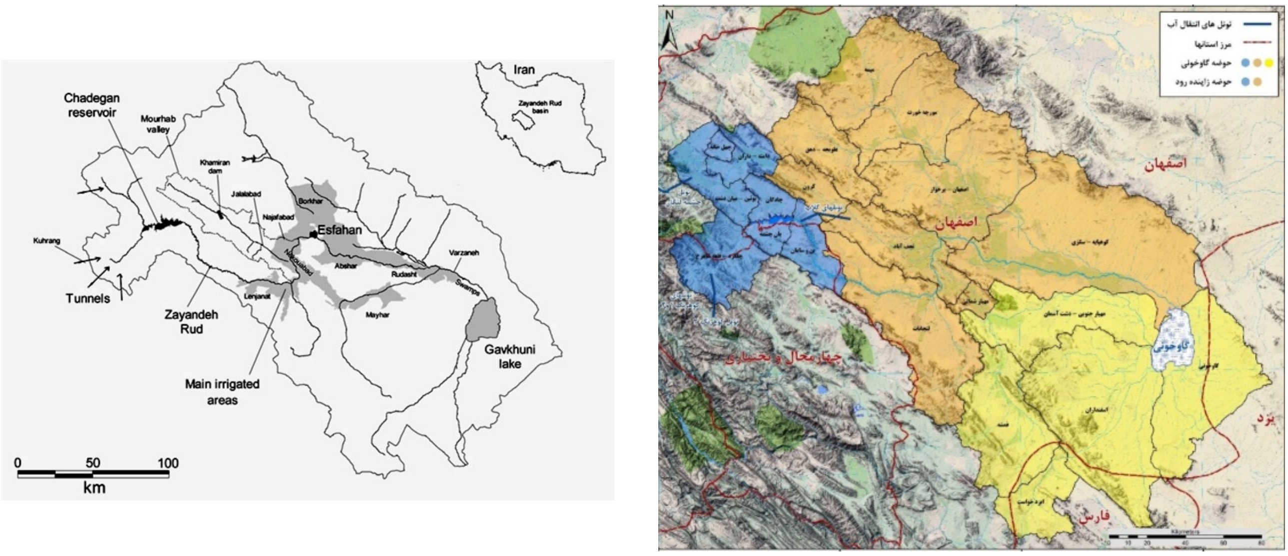


Figure 2-8: Zayanderood River Basin

The length of the river is about 350 km, of which only around 120 km with water, while the rest has turned from a permanent river to a temporary one. The decrease of water flow has begun 70 years ago and intensified during the past 50 years and mostly during the last 20 years. The river hydraulic basin is a closed area, without connection to the sea, spanning over about 41.500 km^2, 2,93% of which is in Isfahan province and 7% in Chahar-Mahal-Bakhtiari province.

The Zayanderood river historically played an important role in the formation of the city of Isfahan. Before the Islamic period, Isfahan was mainly divided into two parts: Jay and Yahudieh. Jay was near the river and there are some documents referring to the palaces facing the river.

In the Buyid and Siljuid era the city of Isfahan has been described as an important city with its unique system for dividing and distributing water for agriculture as well as drinkable one. In the Siljuid period, it has been said that the mentioned two parts have been united to form the city of Isfahan.

Studies show that from the first years after the invasion of the Arabs until the Safavid period, the city was walled having an important area filled with gardens and groves between the fortified town and the river bank. In the Safavid period the capital was moved from Qazvin to Isfahan, and Because of the migrations toward Isfahan, the importance of water for the population increases even then than before.

In this period a comprehensive plan was designed for the city, which strengthened the relationship between town and river. The most important characteristics of the city as part of this plan are: Chahar-Bagh Street, as an axis toward the river, Garden around Chahar-Bagh street as the natural boundaries of the city, Allah Verdikahn or Sio-Se-Pol bridge as the connector element, the Hezar-Jarib gardens at the end of the southern oart of the axis of the Chahar-Bagh, as well as several new districts developed around the river.

Besides, an irrigation network of canals (called “Madi”) was built, which was sourcing water from the Zayanderood river so as to be used to water the gardens in the extended “Madi” area. This network had an impact on the expansion of the city, and new palaces and houses were built along the canals consistently. This organization allowed the creation of a sort of “Garden city” within the city of Isfahan.

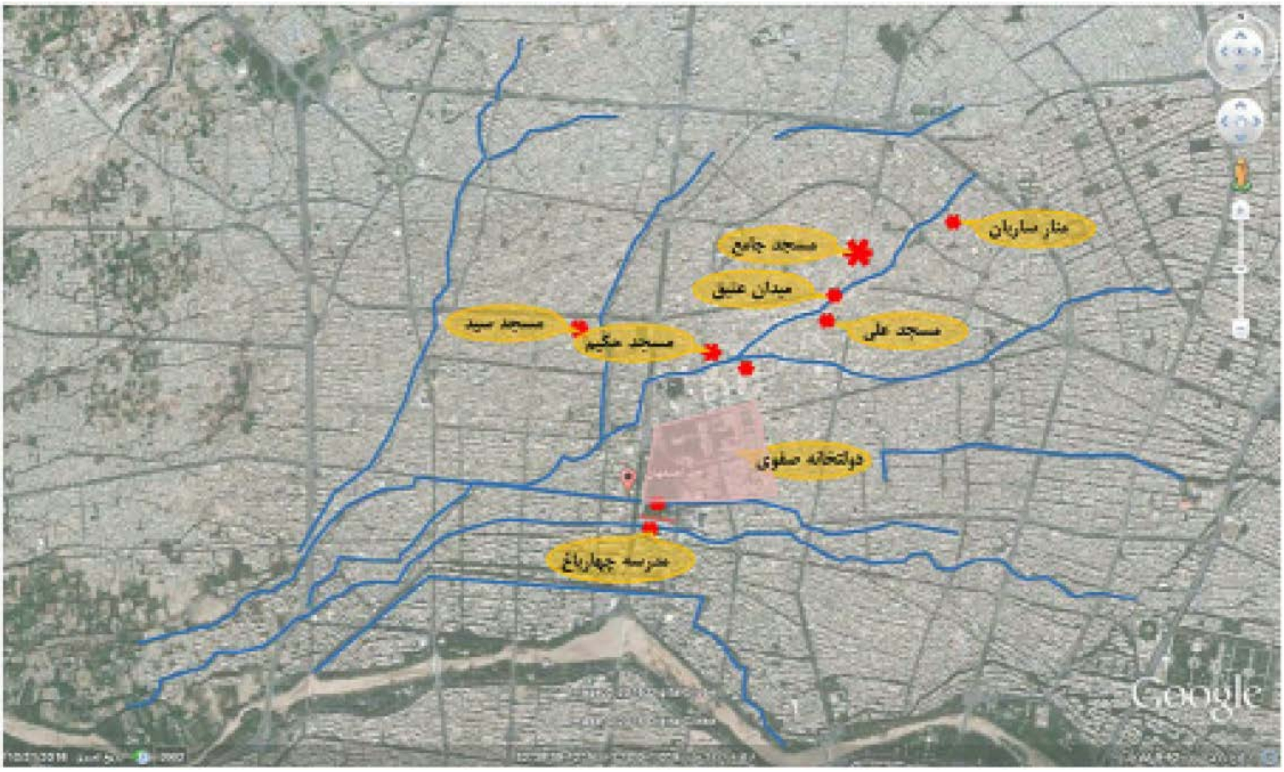
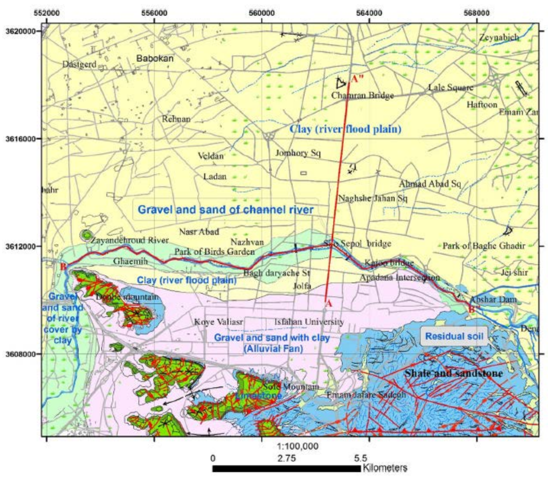


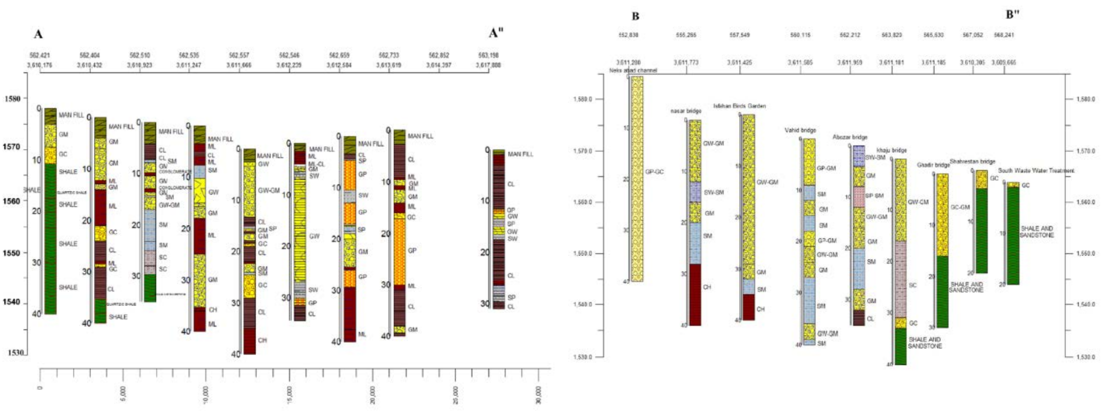
Figure 2-9: The Network of “Madi’s in the city of Isfahan (Namdarian et al., 2016)

2.5. Geological and Geotechnical Situation of the Area

The geological and geotechnical situation of the area under analysis are important to be considered. Within it, a comprehensive study of the seismic conditions would be out of the scope of this research, but a short overview is also given to frame the general condition of the area.



a



b

Figure 2-10: (a) Gelogogical map of the city of Isfahan done by Geological Survey and mineral Exploration of Iran. (b) Results of boreholes along the defined axes on map (Mohammadi, 2020).

Regarding the geological and geotechnical conditions of the city of Isfahan, a study (Mohammadi, 2020), mentioned that Isfahan lies on Jurassic shale and sandstone and quaternary deposits, based on the classification of the soil layers which was done according to the data collected from pits and boreholes (Figure 2-10). A geotechnical and a geological zoning map of Isfahan has been suggested accordingly, identifying seven geotechnical zones (see below) Figure 2-11.

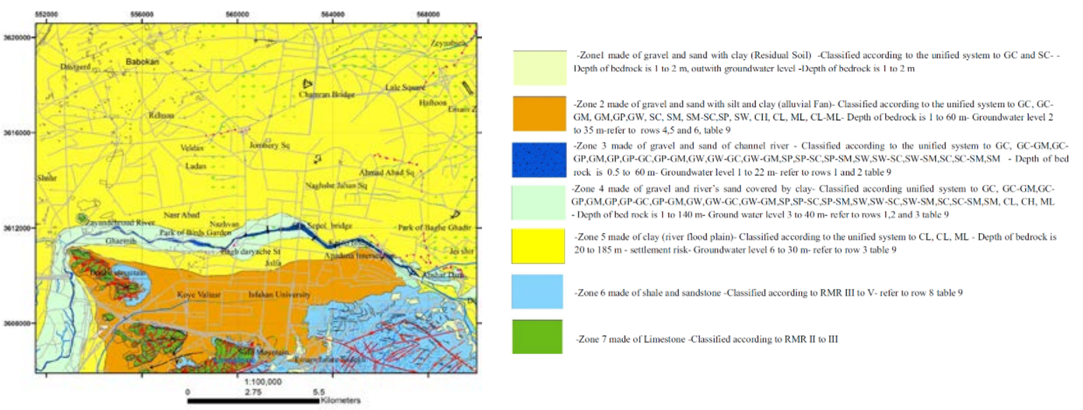


Figure 2-11: Geological Zonation of the city of Isfahan based on the results of boreholes with the map guidance mentioning the types of soil (Mohammadi, 2020).

Regarding the seismic activity, scholars agree that the whole Iranian plateau is being pushed by the Arabian plate from southeast and the Turan region (Euroasian platform) from northwest. The mountain chains emerging within the plateau is a results of these dynamics.

The deformation rate of this movement due to the pressure of plates from both sides is estimated to be from less than 2 mm/yr to 19.5± 2 mm/yr in Iranian plate. Other sources (Alizadeh et al., 2020) have estimated the range of this movement between 25 and 30 mm per year.

According to the Iranian Earthquake Code, Isfahan has medium seismic hazard (Figure 2-12), while a study by (Tajmir Riahi, 2014) shows that the PGA value could vary from 0.125g to 0.265g on the bedrock and from 0.25g to 0.5g at ground surface. This is consistent with the value of 0.25g for bedrock, which is the one recommended by the Iranian earthquake code and the most widely used for calculations of new construction structures. Areas closer to the river have higher ground surface PGA values, due to river sediment beds (loose sand and gravel).

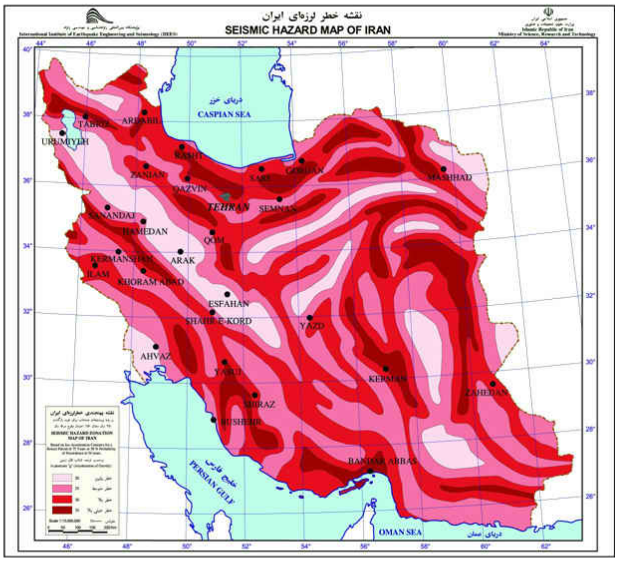


Figure 2-12: Seismic hazard map of Iran (Source: St. No. 2800)

In the study done by Alizadeh et al. (Alizadeh et al. 2020) the risk of earthquake is calculated for the whole city of Isfahan and it is rated from low to medium. For the large part of the city where population and historical buildings are more concentrated the risk is rated as medium.

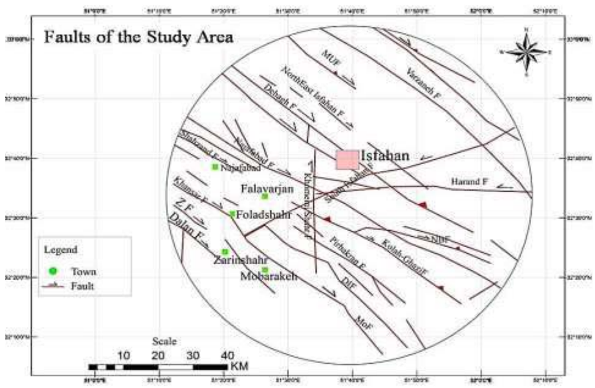


Figure 2-13: Location of Faults around the Isfahan (Alizadeh et al., 2020)

3. Identification of the problem

As mentioned before, the hydrological system of the Zayanderood river has been seriously affected especially during the last two decades. Considering the important role of Zayanderood that is the biggest river of central Iran and supplys water across the Isfahan province for different purposes (e.g. drinking, industrial and agricultural) the possible consequences of peristent droughts would be widespread. These consequences could be classified into: environmental, social and economic (Sarvari et. al., 2019). These are all important factors for sustainable development.

In this chapter, a closer look of the main reasons resulting in the drought related problems, is taken into account, followed by a brief explanation of their effect.

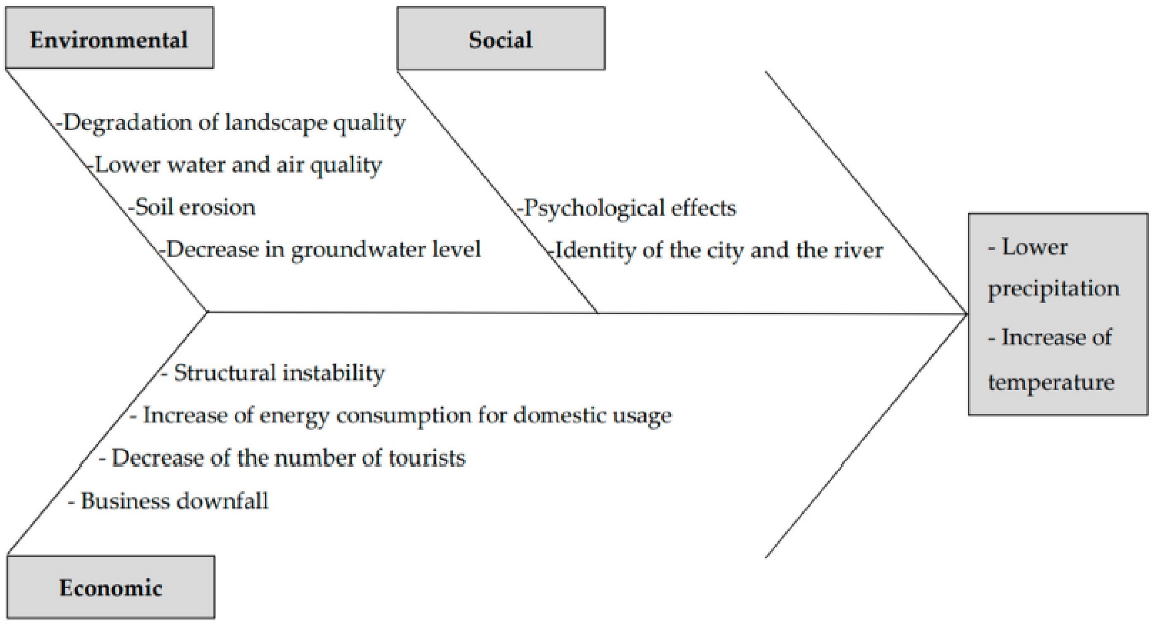


Figure 3-1: Zayanderood Drought Cause and Effect Diagram (Sarvari et al., 2019)

3.1. The Causes behind the Drought

Previously, the Zayanderood was discussed mostly with an emphasis on the relationship between the city and the river. Before entering into details of the drought causes, a short description of the hydrological system of the Zayanderood river and its area is also described.

Zayanderood begins from Zardkooh Bakhtiari, in the province of Chahar-Mahal-Bakhtiari, crossing the region of Fereidan and Fereidoonshar while collecting more affluents and water while flowing towards the city of Isfahan. Having passed nearly 360 km, the river stops in the Gavkhuni marsh. It is important to say that in this path, nearly 2/3 of the areas are irrigable and 1/3 is a catchment area. The historical Zamankhan bridge lays between the catchment and irrigable area. The irrigable area in the study done by Hajian and Hajian (Hajian and Hajian, 2013) contains has a vast surface of nearly 41347 km^2, which is collocated in the middle of Iran and covered by around 40 % of mountainous areas and 60 percent of plains. Moreover, in terms of percentage of terrain in each province that the river passes through, 90.9 percent of which is in Isfahan, 3.4 percent in Fars, 2.3 percent in Yazd, and 3.4 percent in Chahar-Mahal-Bakhtiari province. The slope of the terrain decreases from west to east and the end of irrigation area where the marsh of Gavkhuni is located is nearly on the boundary of the desert area. The main source of water for the irrigable areas are: precipitations, secondary stream in upstream and downstream.

The mentioned percentages in each province presented above is important because it is commonly known that each province often applies its own water management consumption without taking into account any rational criteria to manage the water, which affects the overall state of the river.

Based on the study by Hajian and Hajian, nonpermanent decrease or increase in the precipitation rate has been observed in the irrigable area of the river. For this reason, the major factor involved in the droughts is recognized as the extensive extraction and depletion of water from the river, especially since 2000. The difference between the input (blue line) and output (red line) of water from the irrigable area of the Zayanderood are reported in Figure 3-1, showing this greater differences since 2000 (1380 Persian calendar) which was when the diversion of the water to nearby provinces begun.

Based on the statistics, precipitation changes in the Zayanderood irrigable area does not follow a specific pattern. Thus, it could be inferred that interpretate the problem of the lack of water in the river basin as consequences of the general decrease of precipitation is not correct.´ Another study by Hajian et al. (Hajian et al. 2008) declares that the central part of Iran has some of the lowest precipitation rate in Iran, but the water crisis in this area is due to an unbalanced use of the water resources, especially in respect to their availability and the frequency of drought in this area. This study also mentions the number of illegal wells which extract underground water, in addition to the many legal ones. From these both dwells, drinkable and irrigation water are provided. The groundwater in the city of Isfahan is mostly supported by the water of Zayanderood and in part by precipitation. The increasingly built up areas of the city has also increased the needs for water and drastically affected the underground water level, intensifying the drought of the river. This has resulted in more drought periods and the complete disappearing of the water from the Zayanderood’s bed.

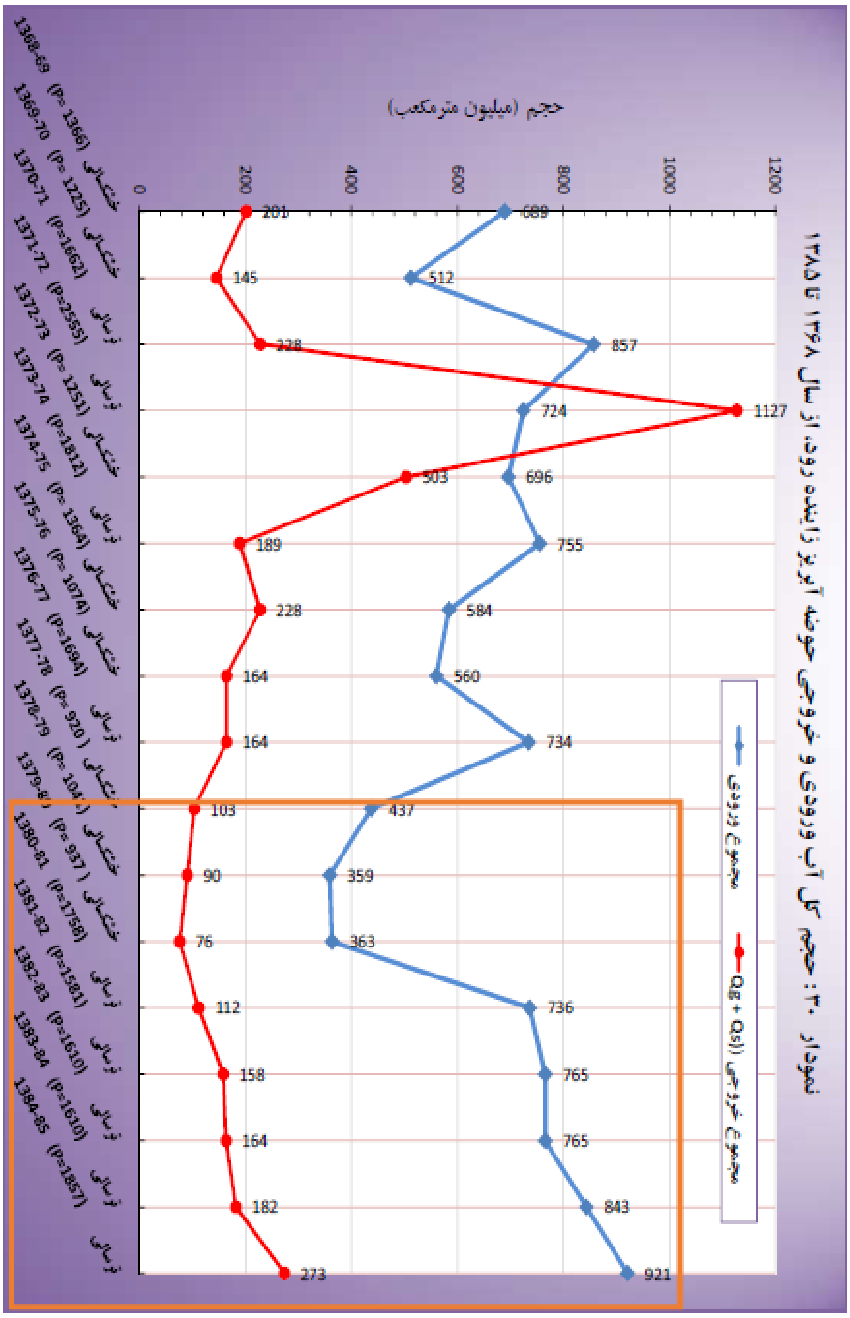


Figure 3-2:Input and Output of Water from the irrigable area of Zayanderood (Hajian and Hajian, 2013)

The Zayanderood water stream does not depend on the city of Isfahan only, as the river and its irrigation basin include a wider region that precedes the city. Since the river sources originate in areas that receive an average annual precipitation rate of 900-1900 mm, it would have been unlikely to estimate the scale of the current drought situation, which are severe as never before. Thanks to the first and second Koohrang tunnel, which carry an average of 250 million m^3 of water, an amount of 700 million m^3 is transferred toward

Isfahan. Although this amount of water (still the creation of these tunnels is also under question) could address to some extent the lack of water in the irrigable area of Zayanderood, it has not helped much because the balance between outlet and entrance of water still is interrupted.

3.2. Environmental Effects of Drought

The lowering of groundwater levels in the soil is one of the main causes of subsidence (also known as “land subsidence”). Natural and anthropic factors may affect the rate of subsidence, which stays for long periods of time an invisible phenomenon characterized by slow settlements on large areas. Sometimes, the term subsidence is also used to indicate sudden ground failures caused, for example, by mining activities or oil extraction.

In cities which are located on top of fluvio-lacustrine deposits (which normally do not have the same thickness of the different layers), subsidence due to groundwater withdrawal, is a hydrogeological phenomenon that threatens them because of the differential settlements and aseismic ground failure (AGF). AGFs are caused by compaction of unconsolidated sediments in fluvio-lacustrine and lacustrine terrains and are recognizable by: land fissure and surface fault. Earth fissure is generated due to tensile failure and surface fault is generated by the movement of blocks, due to differential settlements, parallel to the plane of faults (Figure 3-3). Moreover, since AGFs are result of hydro-geological-anthropic process, their number and size increases with more groundwater withdrawal. (Hernández-Madrigal, 2014)

The presence of water inside the river also affects the underground level, as discussed in a study by Hosseini abri (Hosseini Abri, 2003). In their research, the groundwater level measured was so low in an already difficult drought situation, that even when the farmers who tried to reach the water bed had to dig up until 300 meters in order to have traces of water. This is just to exmplain the entity of this phenomenon.

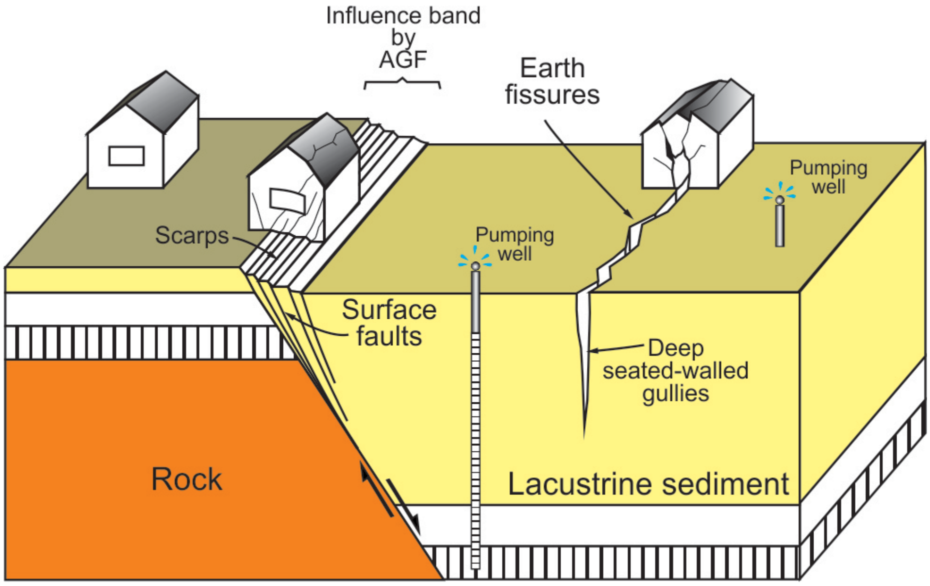


Figure 3-3: Ground Failure induced by extraction of Groundwater (Source:

The dry weather of the city was also balanced by the water flowing in the river bed, since also provided a hiher humidity. Therefore, the lack of water has also an affected on the humidity balance, especially of the areas near the river banks.

3.3. Social Effect

The historical bridges in the city of Isfahan are not only monumental structures, but also important elements of the urban landscape that have been crucial to link environment and people. The architecture of the bridges, the environment and the people are interrelated and interconnected and each of these aspects should be taken into account in order to have a holistic view of the problem, since when any of these aspects change all the others can be affected.

Based on a study by Hanaei et al. (Hanaei et al., 2021), the environmental psychology[2] also affects the sense of social security. The memory of the bridge also affects the social behaviour and public presence in the urban environment. In a study by Ghasemzadeh et al. (Ghasemzadeh et al., 2014) it is mentioned that the impoverishment of natural spaces within the city can alter the interactions between citizens and their surroundings, and for this reason the drought of Zayanderood has drastically affected the way social interaction would normally take place in the adjacent areas of the river. This is important since it is in direct relation with the social health of the people.

[2] Environmental Psychology explains how the environment shapes our individuality and how human beings and environment affect each other.

The identity of a city is formed by socio-cultural as well as environmental factors and are strongly related to its citizen. Human interaction taking place in significant places are important to form memories of that area. Consequently, that place has the potential to become a recognized as a valuable monument, or anyway a valuable social space where people build their memories, in a constant relation between past, present and future. These memories are therefore an intangible but potent part of the identity of the city. Human beings participate in urban life, often performaning similarly to actors or even observers. The river of Zayanderood in Isfahan has historically become a place that included all these factors. The margins of Zayanderood, which are important green spaces of Isfahan, constitute a valuable and highly recognized place for social interaction between the people, but also between the people and the environment.

Figure 3-4: Demonstrationa of People and Farmers in October 2021 Inside the River Near Khaju Bsridge (Source: Farsnews)

Considering the social importance related to the river and its adjacent areas, it could be easily understood that the citizens of Isfahan were dissatisfied by the emptiness of the river bed resulting from the mismanagement and poor policies implemented by the government, In October 2021, a demonstrations took place inside the empty river near Khaju bridge, which were also accompanied by the strike of the farmers for more than a week, even if it was brutally ended by the government.

3.4. Economic Effect

Although drought can be a natural phenomenon, it also has different features and intensity depending on the place where it happens as well as anthropic factors. The economic consequences of drought could be temporary, but also permanent in some cases. There are proofs showing that by 2025, nearly a third of the population of the world will experience the problems related to water scarcity.

Historically ,Isfahan has been experiencing periods of drought, but especially in the last 20 years this has seriously affected the jobs in agricultural sector,. Based on a study by Mahmoodi et al. (Mohmoodi et al., 2022) the economic consequences as a result of the intensity of drought are: the decrease of real estate price, the poorer economic condition of farmers, a reduction of political investments in the areas affected, an increase of dependency from government, and an overall decrease in economic security.

Besides, in urban contexts, ground failure including subsidence results in damages to infrastructures and buildings, including historic ones that are often more vulnerable to this danger. The reports containing the economic estimation of the damages linked to subsidence on buildings state that the approximate scale is around one million dollars. (Hernández-Madrigal, 2014)

What can be inferred from the literature review is that an analysis and categorization of the different causes and consequences of the drought included several and different aspects, and that these aspects are often related to each other.

4. The bridge under investigation (20 pp)

4.1. Khaju Bridge and its current condition

The bridges of Isfahan especially Khaju bridge, have been internationally represented in renowned historic sources such as those by Chardin, Tavernier and Kaempfer. The bridges are mostly mentioned because of their uniqueness and beauty. Moreover, other aspects are also considered, for example in a study done by Luschey (Luschey, 1985) the “water-art” of the Khaju bridge has been emphasized. In general, most of the studies, especially those on Khaju Bridge, and even contemporary ones, have focused mostly on the architectural and urban aspects and none of them have seriously considered a precise structural analysis. Among these studies, one of them discusses the structure of Si-o-Se-Pol Bridge (Ahmadi and Fathianpour, 2016) using GPR method, lacks a thorough structural analysis of the bridge. On the other hand, nothing in the available resources has been done similarly to the latter one mentioned on the Khaju Bridge. Studies on bridges not systematic since they do not provide a comparable and detailed description of the structural condition of the bridges.

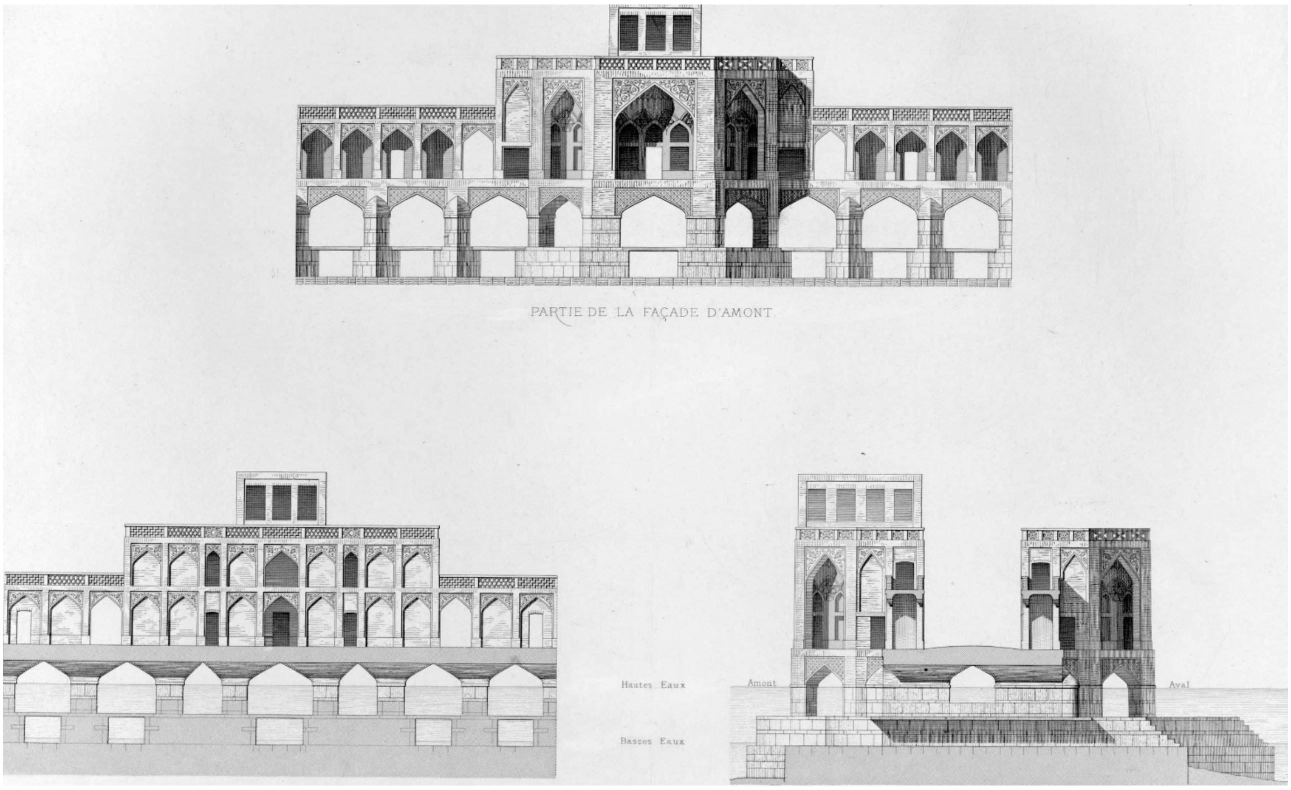


Figure 4-1: Khaju Bridge, Plan and Section by Coste. (Source: Wikimedia.org)

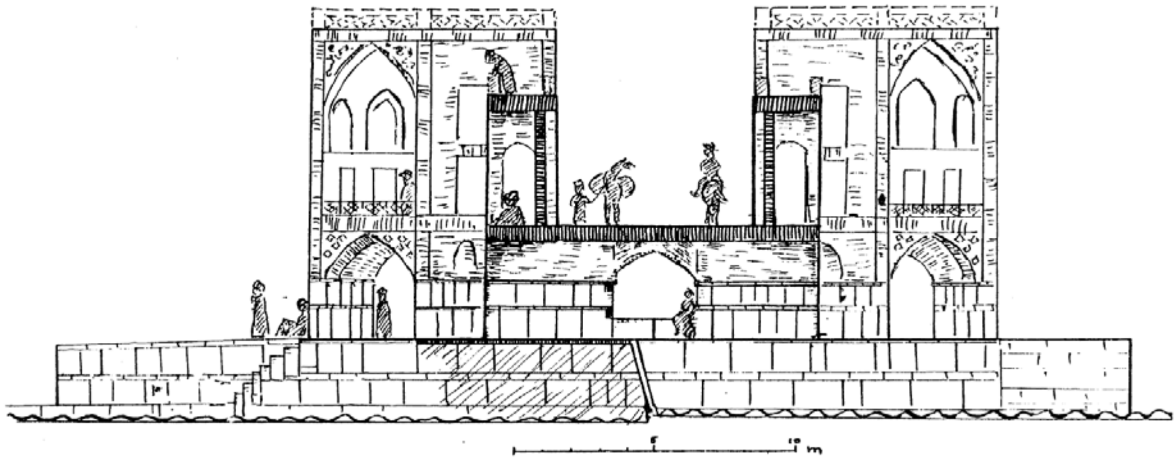


Figure 4-2: Section of Khaju Bridge by Luschey. (Source: Luschey, 1985)

Regarding the problem of subsidence, the literature review does not provide specific research that connects this issue with its effects on the structural status of bridges affected and its possible connections to the phenomenon of drought. A study by Goorabi (Goorabi, 2020), using Interferometric Synthetic Aperture Radar (InSAR) technique, has observed the subsidence through a 5-year period (2014-2019) over Isfahan Alluvium Plain and Zayande-Rood Terrace. The results of this study show the deformation velocity map along the satellite line of sight (LOS). The study states that the alluvium sediments of the Quaternary period cover a large portion of the area. Besides, the clayey and silty layers of the soil reveal a large void ratio and compressibility.

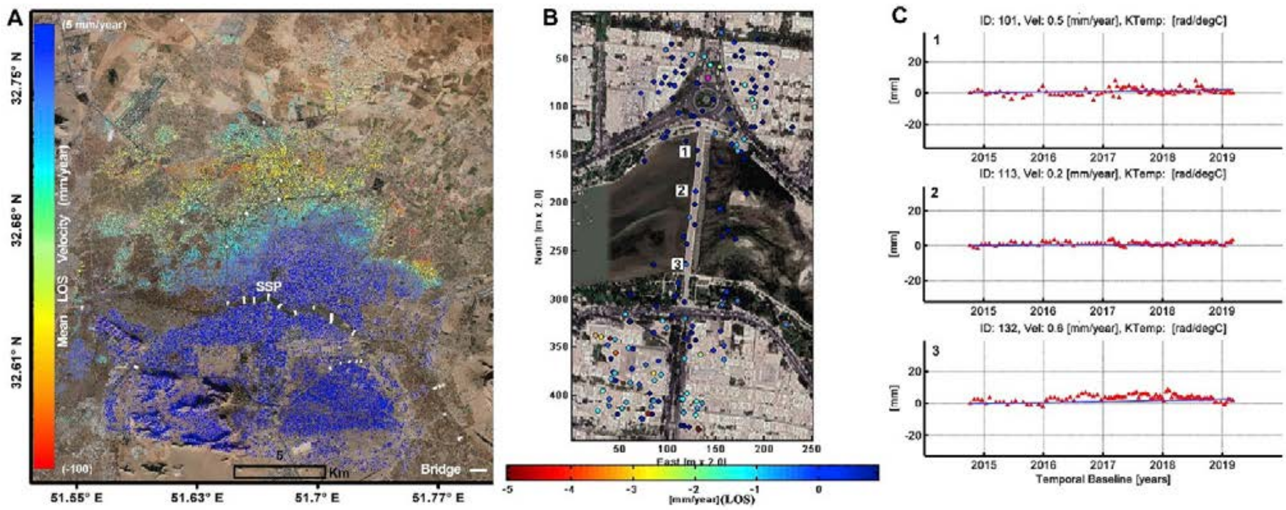


Figure 4-3: Mean LOS Map Overlapping Google Map Image, SSP corresponds to Si-O-Se-Pol bridge and the annual rate of subsidence along the bridge in points 1,2 and 3 are shown on the graphs (Goorabi, 2020)

The study also reveals the subsidence rate of around -100 to +5 mm/year and claims that the subsidence rate in the Si-o-Se-pol has followed a steady status of 0.2 to 0.6 mm/year. This study does not specifically focus on Khaju bridge.

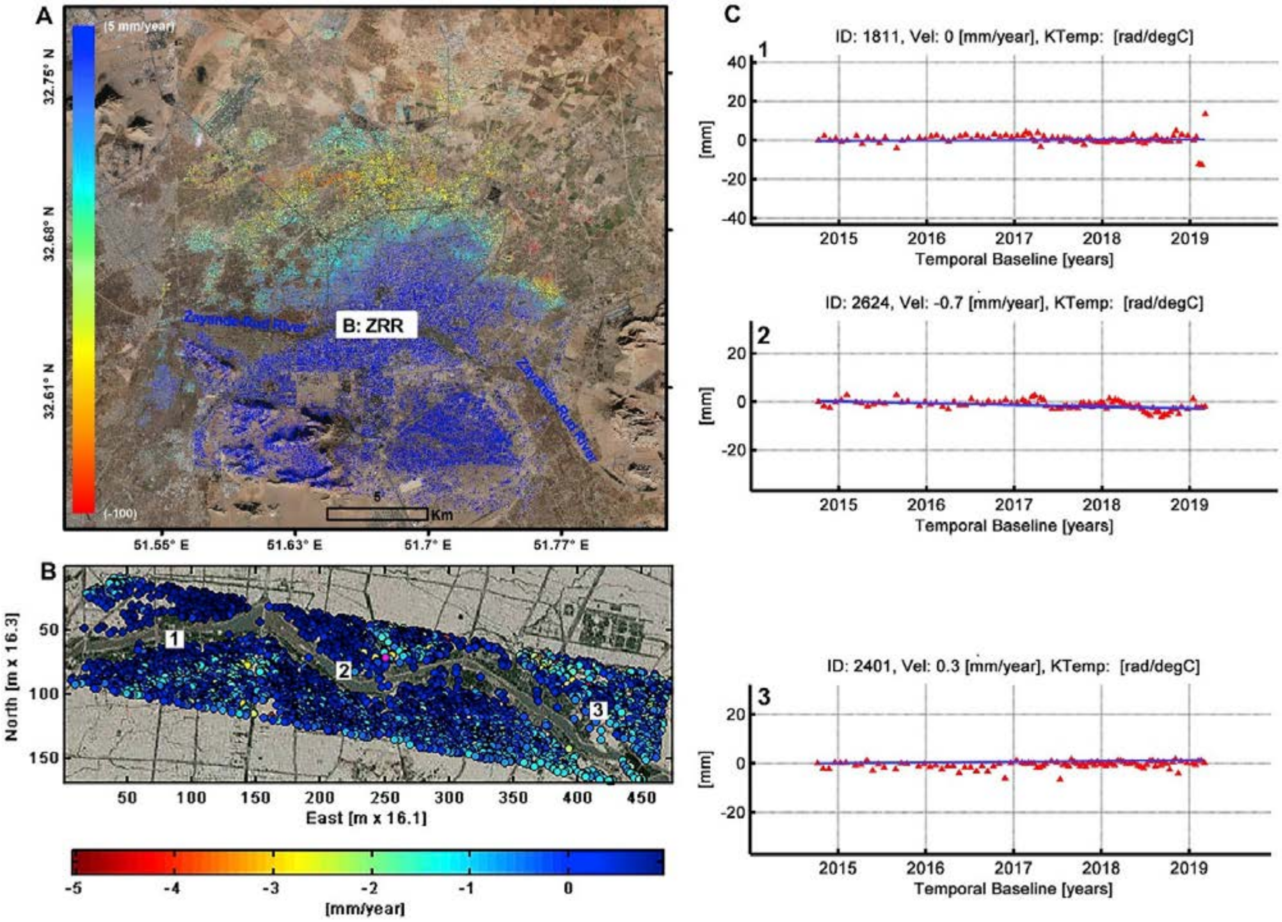


Figure 4-4: Mean LOS Map Overlapping Google Map Image Along Zayanderood, ZRR corresponds to Zayanderood and the annual rate of subsidence in points 1,2 and 3 are shown on the graphs (Goorabi, 2020)

It is also important to mention that the subsidence studies that are done on the area of Isfahan are mostly related to geotechnical issues and the link between them and historical structures, like bridges, seems to be a knowledge gap the literature.

It was not possible to study the Khaju bridge directly due to the reasons already stated (its location and the special situation of Iran in this period that complicated access to the site and archival information), but from the images found on the internet, which are mostly published in the local news, it is possible to understand the presence of cracks on the bridge. This type of damages are present also on other historical bridges, like the Sio-Se-Pol bridge (Figure 4-3 and 4-4).

Figure 4-5: Damages Observed on Si-o-Se-Pol Bridge (Source: ISNA)

Figure 4-6: Cracks that are Recently Obsereve in Khaju Bridge (Source: ISNA)

This study proposes a process to monitor the structure under observation. Consequently, a series of techniques is discussed in order to initiate a critical comparison process useful for the structural analysis of the bridge.

4.2. Monitoring Techniques

The Monitoring techniques for a structure tha can be affected by drought phenomena should be divided into two categories. One regards the condition of the structure and the another regards the the soil analysis. Monitoring techniques help to understand the cause of subsidence, the ground condition and even the scale of possible damages. Some methods can help the structural analysis based on concrete data that can reveal important details of the most vulnerable locations in order to design better solutions for any type of interventions on the building.

4.3. Soil Monitoring techniques

The methods that are used to measure the land elevation, compaction of aquifer, and water level help us have a clearer perception of the rate of land subsidence and in general they could be under the categorization of elevation or elevation-change measurements. Among elevation-change measuring methods, spirit-levelling surveying, interferometric synthetic aperture radar (InSAR), continuous global positioning system GPS (CGPS), could be mentioned that are used for the abovementioned purposes. Methods for water level measurement are piezometers, while ground settlements can be measured using extensometers. In terms of resolution, topographic-levelling and extensometers (resolution of 0.01-0.1 mm) are the most precise, on the other hand, GPS, CGPS (resolution of 3-5 mm) and InSAR (resolution of 1-10 mm) are the least precise ones (Shujin et al. 2016). Based on the situation and the information needed, one or a combination of these methods could be used. (Website of USGS, Science for a Changing World)

4.3.1. Topographic Levelling

Spirit Levelling is the oldest method used for elevation-change measures in terms of subsidence or uplift. This method is generally used for smaller regions (small scales in order of 5 miles or less) and the instruments are installed along roads, aqueducts, and canals. This method as well as being simple is a precise method that was mostly used before the use of GPS surveying method especially when the vertical movement is under investigation. Theodolite or geodimeters are used in this method and the surveyor monitors a point from a reference point using a precis telescope and a marked rod.

Figure 4-7: Spirit Levelling Survey in 1905 (Source: USGS website)

4.3.2. InSAR

Synthetic Aperture Radar (SAR) is a microwave imaging system, and the interferometric approach (InSAR) could accurately measure travel path of radiation. Travel path variation is a function of time and the location of the satellite and measuring the travel path could give digital elevation models and, centimetric deformation of terrain (Ferrati, 2007).

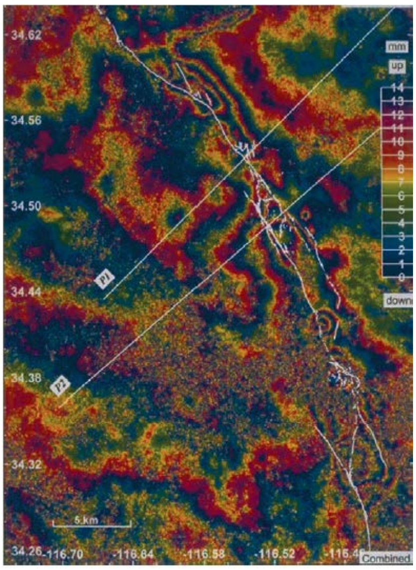


Figure 4-8: An example of post seismic detection by In SAR technique (Ferrati, 2007)

Satellite remote sensing techniques have been already used in natural hazard displacement observations such as earthquake (Figure 4-8), but the use of these techniques in the subject of subsidence and more specifically for historical buildings is still an open discussion. (Gagliardi, 2022)

The basis of the SAR is on the calculation of displacement using the phase change in transmitted signals. The phase of the signals is represented in the Figure 4-9 with this expression that if the slant range from the transmitter to the target and back is stated by $2R$ then the phase of the signal would be calculated by:

$$\varphi = 4\pi R/\lambda \qquad \text{(Equation 4-1)}$$

Where φ is the phase of the wave, R is the distance from the satellite to the target and λ is the SAR wavelength.

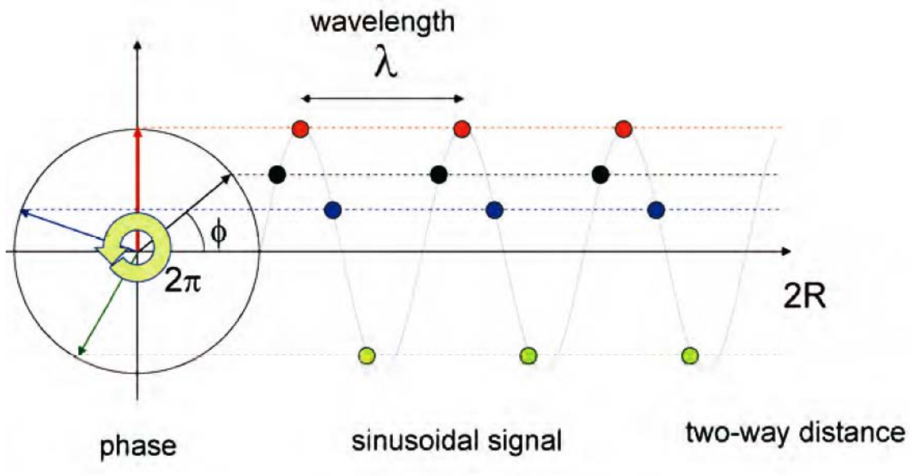


Figure 4-9: Definition of the phase of the wave and its relationship with wavelength and slant range (Ferrati, 2007)

In this regard, since each target is observed in at least two positions (in different times or by different receiver) the variation in phase is corresponded to the difference in travel path.

$$\Delta\varphi = \frac{4\pi\Delta r}{\lambda} = \frac{4\pi}{\lambda}\frac{B_n q_s}{R} \qquad \text{(Equation 4-2)}$$

In case of terrain displacement such as subsidence, landslide, earthquake, etc. another term corresponding to the displacement in the direction of slant range d is added to the previous term for phase variation:

$$\Delta\varphi = -\frac{4\pi}{\lambda}\frac{B_n q_s}{R} + \frac{4\pi}{\lambda}d \qquad \text{(Equation 4-3)}$$

In this case if the digital elevation model is already available, the phase variation could be subtracted from the interferometric phase and the so called differential interferogram could be measured and thus the motion could be obtained.

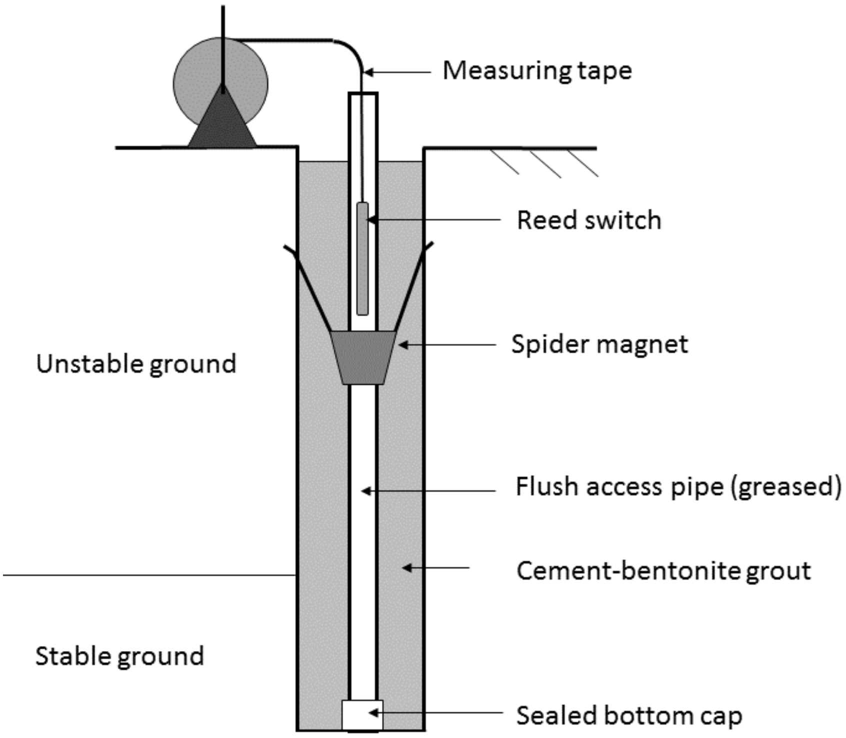
4.3.3. Continuous global positioning system GPS (CGPS)

CGPS technique especially if done in a continuous way could be used to monitor the 3D position of a point on or near the earth's surface. Initially, this method was invented to monitor the tectonic displacement, but it has been used also for other purposes such as subsidence monitoring. In general, this system gathers information every 15 seconds and through processing the daily position of a point is obtained.

Figure 4-10:

4.3.4. Extensometer

These instruments are able to measure 1 dimensional displacement and are used mostly for monitoring expansion and compaction of aquifers. Their mechanism works in a way that these measurements are done up to a specified depth. The instrument could have different models, in each case of which, the specified depth from which the displacements could be measured is because of inserting anchors in the soil. as it has been shown in Figure 4-11.



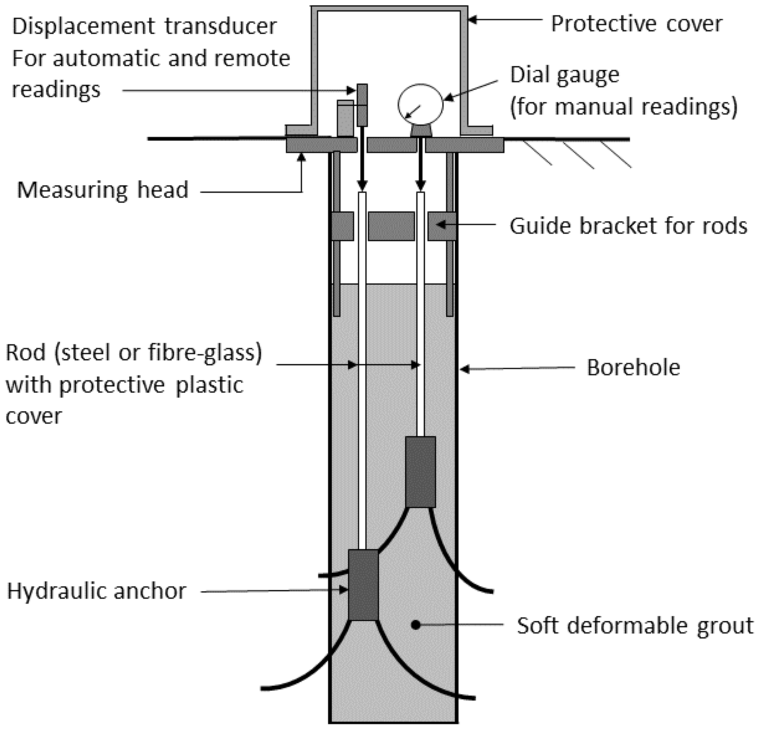


Figure 4-11: Extensometer Types. (Up) Probe Extensometer, (Down) Rod Extensometers. (Source: geo-obseravtion.com)

4.3.5. Piezometer

Piezometers are used for monitoring underground water level. The instrument could have different types but in general it is composed of an inserted tube which is open to the atmosphere and extends to the soil surface. The tube is placed in the soil under the water table level. The perforated bottom of the piezometer allows the water to come inside the tube until it reaches the unconfined level. Using steel tape, the water level is measured with respect to the soil surface (Or et al., 2022)

The relationship between river-aquifers has a lot of complexity, the state of aquifers affects the flows of the rivers in their extremes (high and low flows), which has been confirmed in different contexts. A network of piezometers can monitor the groundwater level for a long time and their database could be used to have an estimation of the river system, as well as its use for subsidence monitoring due to the change in the groundwater level (Pelletier and Andréassian, 2023).

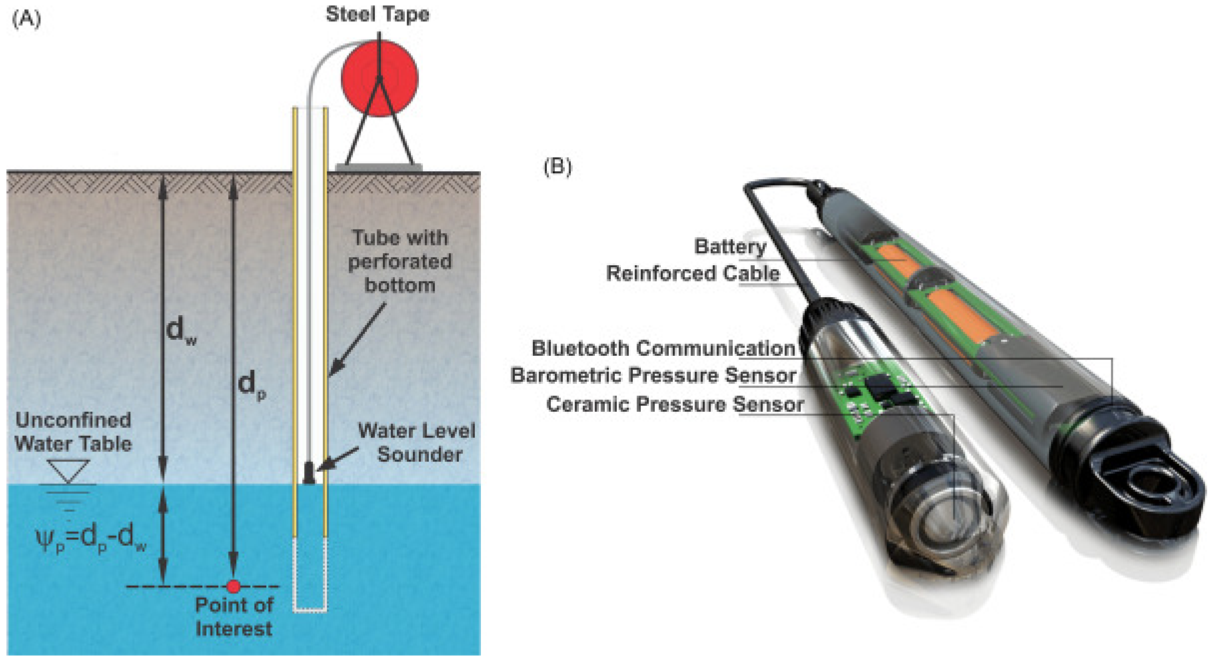


Figure 4-12: Mechanism of Piezometers (Or et al., 2022)

4.3.6. Optic Fibres

Distributed fibre optic sensors (DFOS) are being commonly used recently in order to obtain a real-time monitor and they could even provide an early notice of hazards related either natural or anthropogenic such as land subsidence, and earth fissure. The assumption for this method is that the properties of the surrounding affect the properties of fibre and therefore by investigating the properties of fibres we can obtain the changes in the surrounding environment. When an optical signal travels through fibres the temperature and strain can influence the frequency and intensity of scattered signal. The properties that could be measured by fibre optic sensors with high accuracy includes, displacements, earth pressure, soil moisture, pore water pressure, and variation of temperature. The use of this method using stress sensing cables in boreholes was done in a project in China, Suzhou. The cables were supposed to monitor displacement and were laid vertically in the boreholes. In another project in Japan, these fibres were used to monitor the land fissure. (Gambolati and Teatini, 2021)

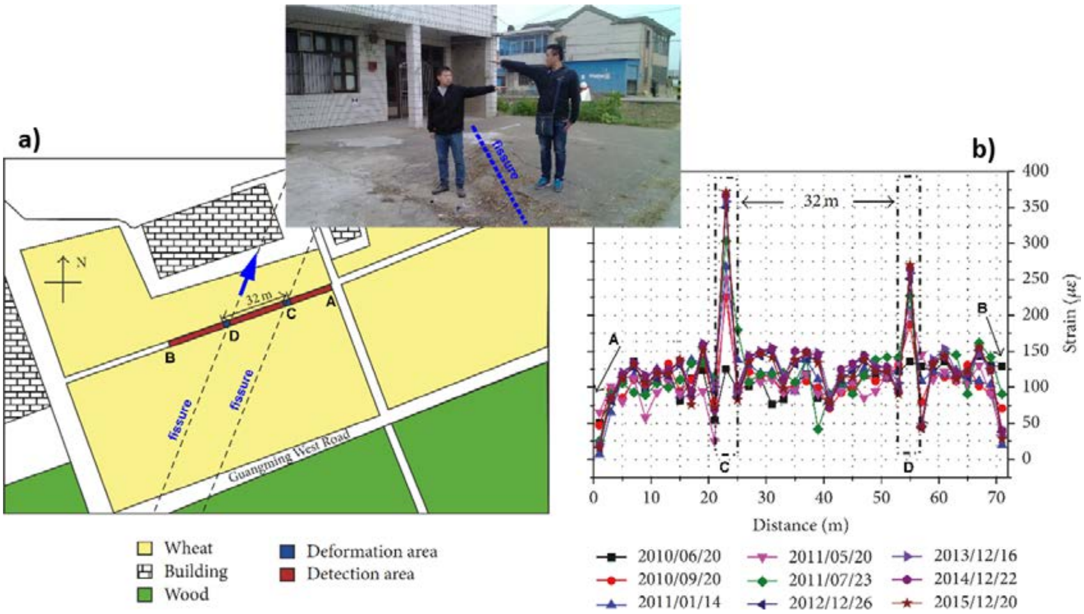


Figure 4-13: Earth fissure Map using DFOS (Gambolati and Teatini, 2021)

4.4. Structure Monitoring Techniques

The identification of damages in structures which basically defines the state of the healthiness of the structure could be done by different methods. The methods that are used to identify damages and anomalies, range from conventional methods including visual inspection, to techniques that combine different fields (computer science, electronics, mechanical engineering, material science) with civil engineering. Structural Health Monitoring is the common name used for multidisciplinary techniques.

Monitoring a structure in general is based on the level of knowledge we need. According to the study by Gharebaghi et al. (Gharebaghi et al, 2022) these levels are mentioned as mentioned in table 4-1, the first two levels are classified as diagnosis and the others as prognosis steps.

Besides according to the same study, structural health monitoring could have a local or global approach in terms of the scale of the structure. For example, non-destructive tests are local tests that can give information about the location of damages and monitoring a specific part of the structure. Also, global techniques that are used to assess the entire state of the structure could be used also to gain information about a specific part. Global techniques are generally based on vibration characteristics like natural frequency. In general, dynamic techniques could be more accurate for the detection of sudden or gradual changes.

Table 4-1: Description of Different Levels of Monitoring (Gharebaghi et al, 2022)

Level	Description	Explanation
Level 1	Identification	determining the existence of a defect on a global scale.
Level 2	Localization	determining the location and coordinates of the damage.
Level 3	Assessment	determining the intensity of damage in various components.
Level 4	Lifetime prediction	estimating the structure’s remaining life.

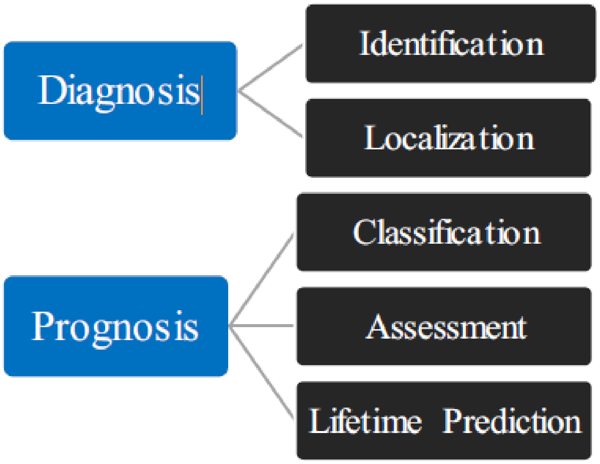


Figure 4-14: Damage Identification Levels ((Gharebaghi et al, 2022)

For historical buildings due to their specific condition and their values non-destructive or minor-destructive methods are used. In the following, non-destructive or minor-destructive tests that are used mainly for historical bridges are explained.

4.4.1. Providing Descriptive map through visual Inspection

The first and most important in-situ test is the visual inspection to register all the visible damages of the structure and their location. It is also followed by photogrammetry of the structure to technically locate the damages.

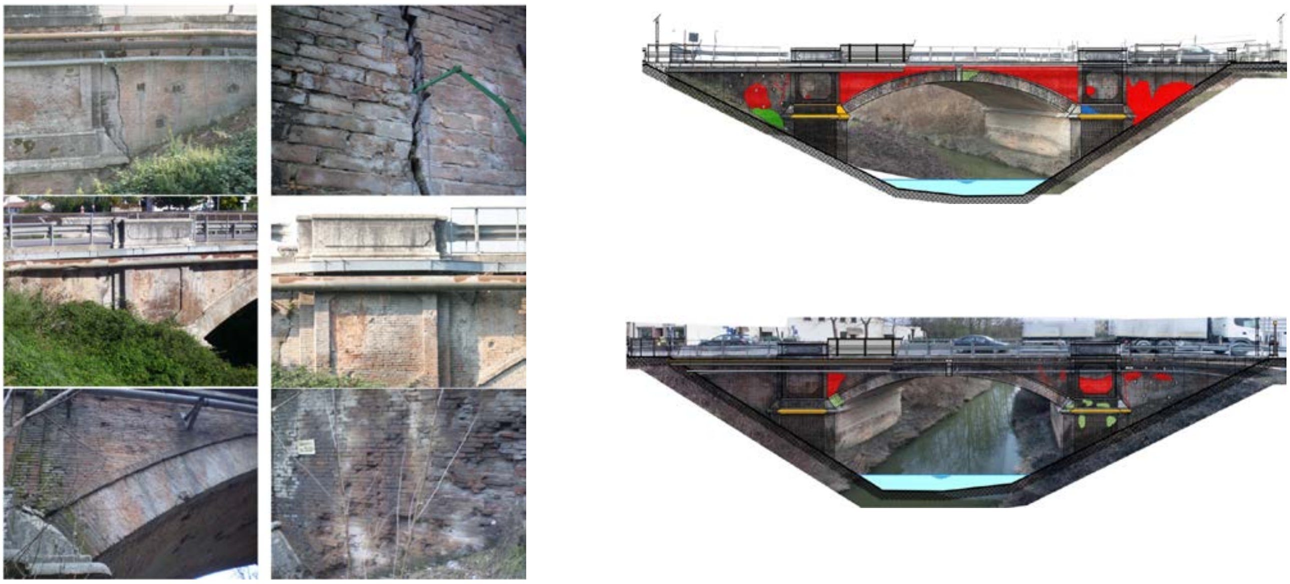


Figure 4-15: visual inspection for providing a damage catalogue (Bergamo, 2015)

Moreover, a descriptive list for structural elements, damage, materials, and an estimation of the cause of damages should be provided at this level. In this phase suggestions for using NDT test should be provided to provide more information. (Binda, 2006)

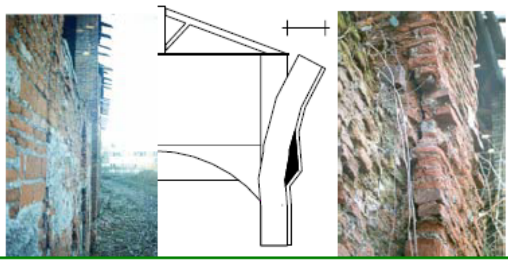
DAMAGE: Vertical cracks on the middle part of a brick masonry built in column causing detachment of a layer.
Structural element*: Solid masonry built in column.
Description: Vertical cracks are evident on separating the external part of the column.
Origin(s): Due to excessive horizontal and vertical loads on top of the column which at first cause rotation of the upper part of the column at the upper floor. The lack of protection caused the rain to go through the column. Salt crystallisation and frost-defrost action caused the loss of material and the detachment (expulsion) of a thick layer of the external part of the built in column.

Measurement Parameters: depth, width and length of the crack over time; geometrical dimension of the pier, masonry composition, deformation, out of plan and inclination of the pier; state of stress; strength., acting loads, radar reflections
Applicable Non Destructive Techniques: geometrical and photographic survey, sonic tests, radar

Figure 4-16: An example of description of damage and building characteristics (Binda, 2006)

Since experience could also be important to give a general idea of the situation of the building, previous studies done on historical buildings could be useful. As an example, the result of a project named ONSITEFORMSONRY a strong knowledge base, based on the tips mentioned above is also provided as Standard Damage Catalogue and includes list of structural typologies and Related requirements, with more than 100 case studies. In this catalogue the classification of structural typology and damages are based on the information provided in the table below.

Table 1: Criteria for classification of structural typology and damages in visual inspection (Binda, 2006)

Criteria	Classification
Classification of structural Typology	Typology: building, bridge, etc. Structural Element: arch, vault, wall, dome, etc. Characteristics of masonry structure: construction technique, history Masonry cross section
Classification of damaged based on their origin	Damage because of material deterioration. Moisture Wind and air pollution Damage because of mechanical Effects: Traffic and live loads Settlement and thermal deformation Dynamic actions

It is also useful to mention that in this standard the information could give an estimation of which of the investigation techniques is useful for gaining a specific evaluation. (Binda, 2006)

4.4.2. Crack Width and Tilt Sensors

Crack sensors mostly monitor the changes in the crack width and tilt sensors observe the inclination that could be induced in the buildings due to subsidence. The instruments for monitoring the cracks or changes in the inclination of building could vary in types but it could be useful to use online methods to have a continuous observation of the situation of the building which provides useful information.

Figure 4-17: Tilt Meter (Source: Emcardio.com)

Figure 4-18: Crack Meter (Source: Emcardio.com)

4.4.3. Infra-Red Thermography (IRT)

The mechanism of thermal camera which is shown in Figure 4-19 works in a way that the heat sensor inside the camera is sensitive to slight differences in temperature and the image called thermogram is created with the information on the distribution of temperature.

It is possible to detect moisture by this technique because of the cooling nature of evaporation which results in intensified temperature difference. The detection of diffusion of water in the masonry done by IRT (Infra-Red Technique) is fundamental for the decay analysis and qualitative information about the presence of water is obtained. Moreover, with the IRT it is possible to calculate evaporation flux considering the variation of surface temperature. The use of IRT in this way is categorized under the passive class.

The use of this method could help us understand better the texture of masonry, difference in materials, possible structural components and other information which based on the organized survey for the study of bridges could be used.

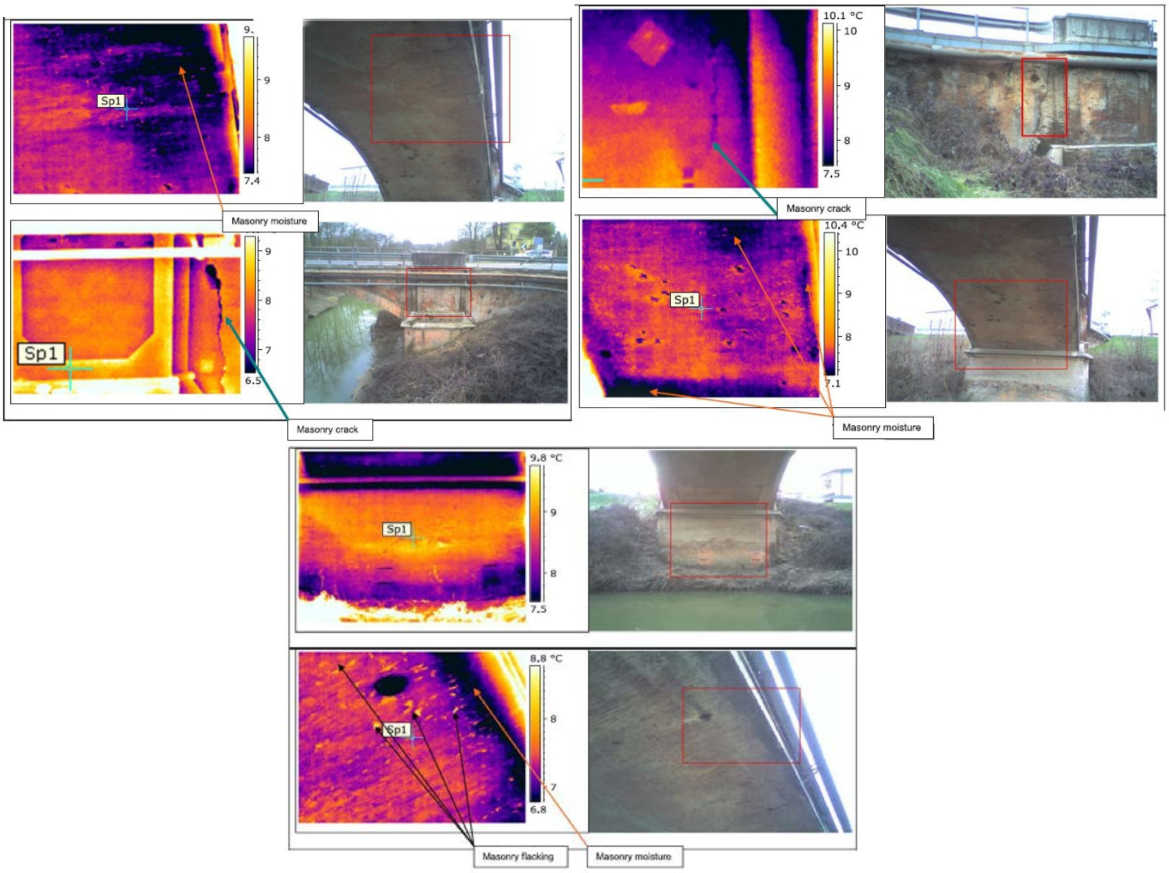


Figure 4-19: Example of IRT investigation with the information provided.

4.4.4. *Ground Penetration Radar Test (GPR)*

Ground Penetration Radar test or GPR is a non-destructive technique using electromagnetic waves to detect features beneath the surface. The technique uses this fact that the velocity of electromagnetic waves is affected by the electric and magnetic characteristics of the mediums through which it passes (reflected or refracted). For example, in the case of changes in salt content, humidity, metal elements, separated surfaces, hollow cavities the waves are reflected and therefore detectable by GPR. In this technique the depth of penetration is controlled by frequency, the lower the frequency the deeper is the penetration of waves.

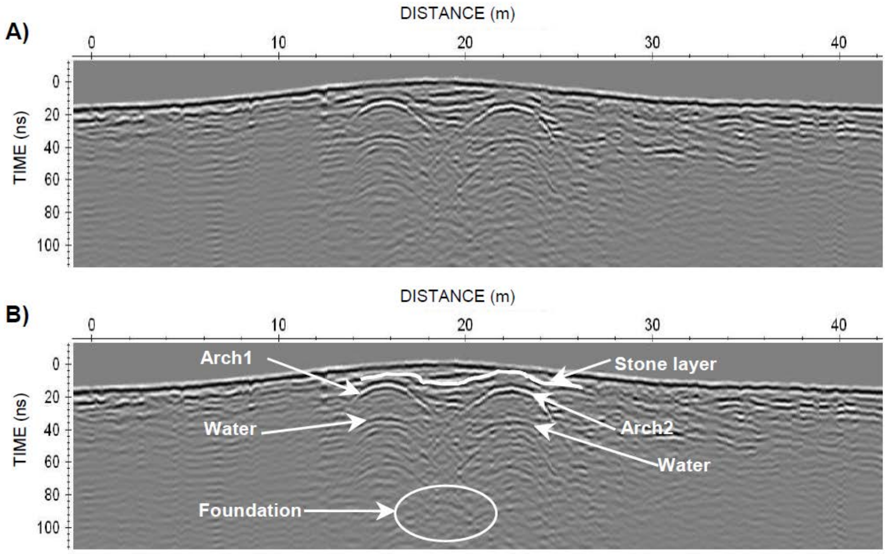


Figure 4-20: An example of detection of different elements by GPR (Carracelas, 2010)

4.4.5. Sonic Tests

Sonic test is a non-destructive (NDT) test and is based on the propagation of Sonic Elastic waves emitted by hammers for sonic test and received by accelerometers, widely used to investigate historic buildings. When the elastic wave is received, they are transmitted to electric signals by piezoelectric device and these signals are shown in a time-amplitude graph by specific software.

Sonic tests use lower frequencies compared to Ultrasonic method and thus can be more useful for obtaining information for massive structures because of longer depth of penetration, the reason is that higher frequencies scatter and do not reach deeper. This also results in longer wavelengths and lower resolution. It should be mentioned that the velocity of sound waves is fixed in a medium and is determined by the physical and mechanical properties of the material. The relation between velocity, frequency and wavelength could be expressed by the equation below:

$$V = \lambda f \qquad \text{(Equation 4-4)}$$

Where V is the velocity, λ is the wavelength and f is the frequency. The velocity of the wave can be simply calculated using the formula:

$$V = \frac{d}{t} \qquad \text{(Equation 4-5)}$$

Where, d is the distance and t is the time. Considering the mentioned notes about the velocity of sound waves the change in the velocity can identify information about the material properties. The highest velocity corresponds to the homogenous material and as the boundaries between material or voids inside the medium increase, the velocity of wave decreases.

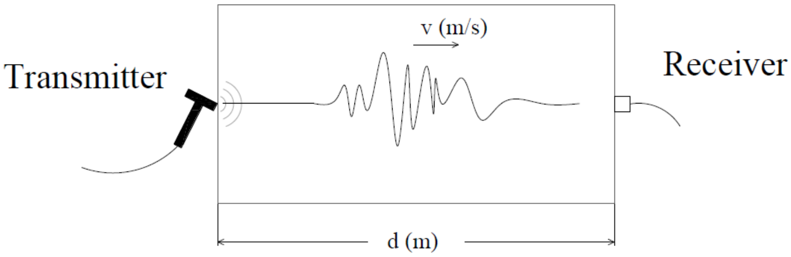


Fig. 11: Direct sonic test (Manning, 2014)

There are three classes of this test based on the location of transmitter and receiver, which is also true for ultrasonic tests, Direct, semi-direct and indirect which are also shown in the Fig. 12. Direct one is when the transmitter and receiver are placed opposite to each other at the same level, semi-direct and indirect the position of the receiver and transmitter is on adjacent and same side of the wall respectively.

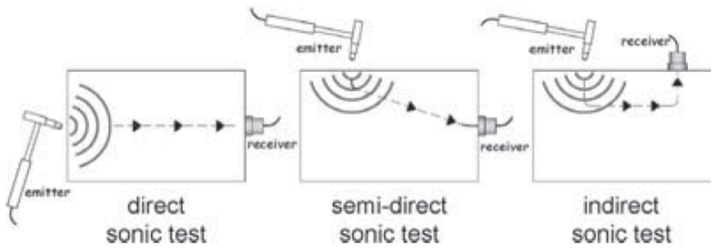


Figure 4-21: Sonic and Ultrasonic classification based on the location of transmitter and receiver (Cantini, 2016)

If the material is isotropic and uniform, the velocity of waves in the body could be used for evaluation of Elastic Modulus. In general, the time of propagation of elastic waves are affected by the properties of the medium through which waves pass. According to ASTM the Elastic Modulus in this case is the Dynamic Modulus of Elasticity. And it can be applied to materials having nearly uniform structure like stone, compact brick, and concrete. The result of this technique is used for a specific location through which the wave has propagated (between emitter and receiver). Thus, normally the sonic test is accompanied by a grid map (Figure 4-22) with slightly near distance to give a more inclusive information about the masonry. To interpret the results of the test, deep knowledge of the test is required. (Cantini, 2016)

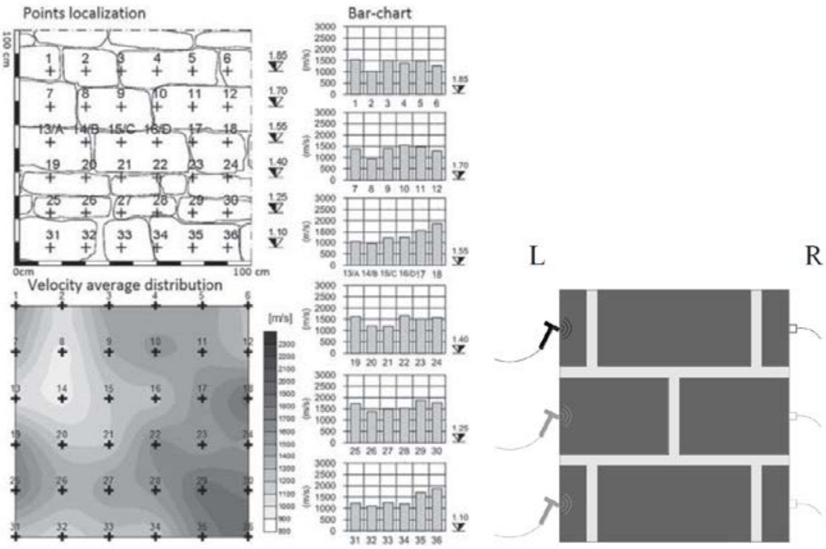


Figure 4-22: Direct sonic test general layout. Left: an example of a grid map. (Cantini, 2016). Right: location of transmitter and receiver

4.4.6. Ultrasonic Technique

Ultra-sonic like Sonic test, is categorized under non-destructive techniques. This technique uses higher frequency waves in Ultrasonic range and to do so an electronic transmitter should be located on the masonry surface.

Ultrasonic tests, because of using short wavelengths could not be useful for large and non-homogeneous bodies. Therefore, Ultrasonic tests are mostly used for the purpose of damage detection in bodies of single material. The classification of the test based on the location of transmitter and receiver, as mentioned before, is the one used also for the Sonic tests. (Cantini, 2016)

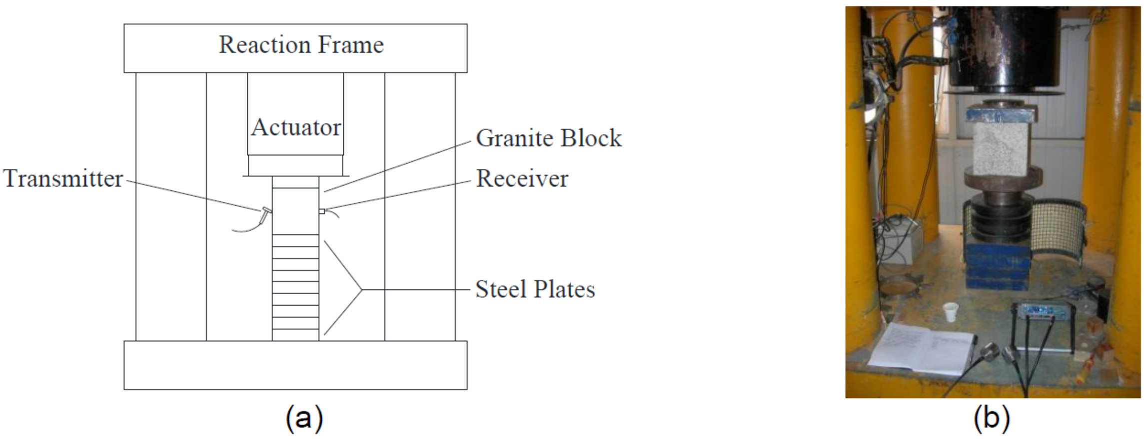


Figure 4-23: Ultrasonic test setup. a) schematic representation. b) laboratory test setup. (Manning, 2014)

On the other hand, a study (Manning, 2014) states that the Ultrasonic test, was mainly focused on the determination of geometric characterizations of masonry as well as damages, cracks, and faults. Moreover, the surface of the masonry affects the result so that even small voids can influence the outcome, since the high frequency waves are not able to pass voids. The resolution of the information obtained by this technique is very high so that defects in the size of (2.5-5.0 cm) could be detected but only if the material is homogenous and has few numbers of defects. It has been also stated that there are efforts in studies to link the Ultrasonic wave velocity with the Modulus of Elasticity and Compressive Strength of the masonry.

4.4.7. Flat Jack

Flat jack test is categorized under minor-destructive tests which requires a removal of a small portion of bed joints and in some studies, it has been mentioned as non-destructive test (Gregorczyk, 2000). The test has been primarily used in Rock Mechanics field and then brought to the field of masonry in the early 80s. there has been also standards that are developed for this kind of technique such as ASTM (American) and RILEM Standards LUM.D.2 and LUM.D.3(European).

Flat jack is basically a thin envelope which is pressurized by oil or water and has different shapes based on the function and dimension of the slot and the properties of masonry being tested. Curved envelopes are used for slots cut by a circular saw and the rectangular ones for slots being emptied by hand or stich drilling. The flat jack should completely fill the slot and if not, shims are used to fill the complete thickness.

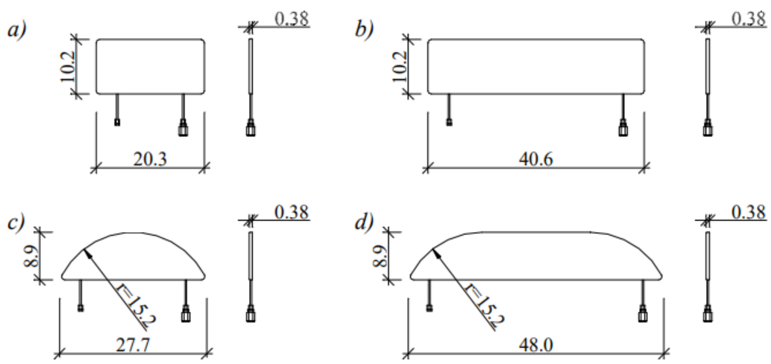


Figure 4-24: Different configuration of flat jack (Gregorczyk, 2000)

Single Flat-jack tests measure the local compressive stress in masonry and are based on the removing partial local stress, followed by controlled imposed stress. The gauges are also fixed to the defined points on the masonry and a place between the heads of the gauges is selected to be cut. Cutting will decrease the distance between gauges and reliefs partial stress. The envelopes are inserted as soon as the slots are prepared, and hydraulic pressure is implied. The pressure is normally more than the actual stress because of the stiffness of the Flat jack, this is also calibrated in the interpretation of the data. The assumptions in the test are as follows:

- The stress in the location of the test is compressive.
- The surrounding material is homogenous.
- The deformation over the slot is symmetric.
- The stress over the slot is uniform.
- The value of the stress compared to compressive strength is in the state that the masonry acts in its elastic state.

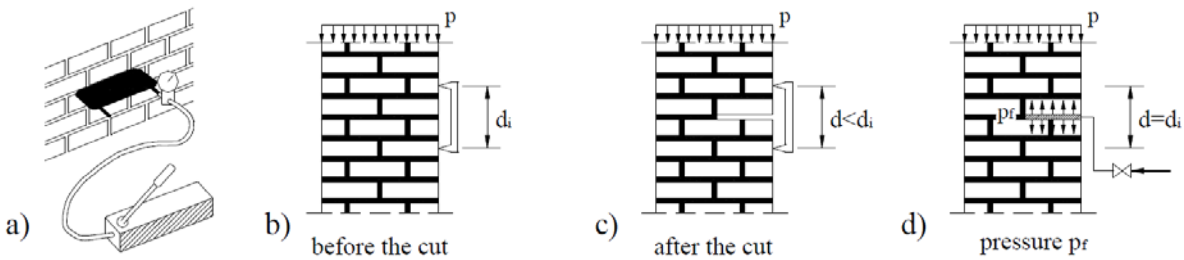


Figure 4-25: Stages of flat jack test (Gregorczyk, 2000)

4.4.8. Double Flat-Jack

Double Flat-jack is also like single Flat-jack categorized in minor destructive tests or even in some cases has been considered as non-destructive because of little intervention needed. In this technique two envelopes are inserted inside masonry and in this way a part of the body is isolated as a specimen, so that is assumed to be unstressed. As the envelopes are inserted a uniform stress is imposed on the part of the masonry in between and with the measurements of the gauges fixed between two envelopes the stress-strain graph could be obtained and the Young Modulus is inferred from this graph. Moreover, cyclic loading could be done. If the strength of the masonry is lower than the maximum pressure capacity of the instrument, the compressive strength of the masonry could also be measured (Gregorczyk, 2000). During the test the displacements related to each step of pressure increase is measured. The stress-strain diagram could be obtained from the test and therefore the Modulus of Elasticity could be measured. (Pinho, 2021)

The calculated stress will be calculated using the following formula:

$$\sigma = k_m . k_a . p$$

Where p is the pressure imposed by the instruments. This formula which applies for both single and double flat jack, states that the pressure imposed by the instruments should be calibrated by multiplying the measured pressure by coefficients corresponding to the features of the jacks (k_m) and corresponding to the ratio between the area of the ack and the area which is cut (k_a).

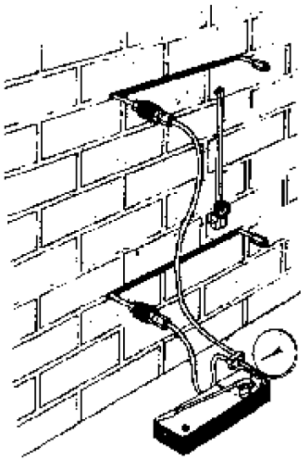


Figure 4-26: Configuration of double flat jack (Gregorczyk, 2000)

4.4.9. Double Punch Test

This test is categorized as a minor destructive technique as it involves removal of a small part of masonry and lies on the principle that the compressive strength of masonry is related to the compressive strength of mortar and brick. This test could be done on the existing masonry mortar or the one that is made in laboratory similar to the historic mortar, but it is obvious that the one done on existing mortar is more reliable. In the case of doing the test on existing mortar, sampling is needed. There are standards such as UNI 6131: 2002 and UNI EN 12504-1: 2002, which are basically for concrete structure but could be used for masonry, where the number and size of specimen are defined. Coring masonry could be useful for samples of brick and mortar.

Figure 4-27: Extraction of cores (Benedetti, 2020)

The samples for mortar are cut into standard measure and put under the double steel punch test. There are studies which have developed relations between the double punch compressive stress and standard compression tests.

Figure 4-28F: Core samples and cutting mortar layer in standard size for double punch test

On the other hand, also in standards like Eurocode there are relationships between the compressive strength of brick and mortar and the compressive strength of masonry. These relationships are developed for new masonry, and historic ones based on the situation of masonry there would be a coefficient to be multiplied to obtain the strength of a historic masonry.

$$f_k = K f_b^{0.7} f_m^{0.3} \quad \text{(Equation 4-6)}$$

$$f_m = 0.555 f_{mdp} + 3.068 \quad \text{(Equation 4-7)}$$

Masonry Unit		General purpose mortar	Thin layer mortar (bed joint ≥ 0,5 mm and ≤ 3 mm)	Lightweight mortar of density	
				$600 \le \rho_d \le 800$ kg/m^3	$800 < \rho_d \le 1\,300$kg/m^3
Clay	Group 1	0,55	0,75	0,30	0,40
	Group 2	0,45	0,70	0,25	0,30
	Group 3	0,35	0,50	0,20	0,25
	Group 4	0,35	0,35	0,20	0,25
Calcium Silicate	Group 1	0,55	0,80	‡	‡
	Group 2	0,45	0,65	‡	‡
Aggregate Concrete	Group 1	0,55	0,80	0,45	0,45
	Group 2	0,45	0,65	0,45	0,45
	Group 3	0,40	0,50	‡	‡
	Group 4	0,35	‡	‡	‡
Autoclaved Aerated Concrete	Group 1	0,55	0,80	0,45	0,45
Manufactured Stone	Group 1	0,45	0,75	‡	‡
Dimensioned Natural Stone	Group 1	0,45	‡	‡	‡
‡ Combination of mortar/unit not normally used, so no value given.					

Figure 4-29: Values of K

The Equation 4-6 is applied to obtain the compressive strength of the masonry out of compressive strength of mortar and brick, where f_k is the characteristic compressive strength of masonry, f_b is the normalized mean compressive strength of the blocks in the direction of the applied load, K is the constant (Figure 4-9) and f_m is the compressive strength of the mortar, while the Equation 4-7 is for gaining the compressive strength of standard sized mortar f_m out of compressive strength that is obtained out of double punch test f_{mdp}.

4.4.10. Splitting test on cores with rotated mortar layer

This technique as a minor destructive technique are done on the cores that contain a layer of mortar in the middle. The several times changing the angle of inclination of mortar. Due to the inclination shear and compressive stress are produced and thus the results could be interpreted on the Mohr-Coulomb circle. (Benedetti, 2020)

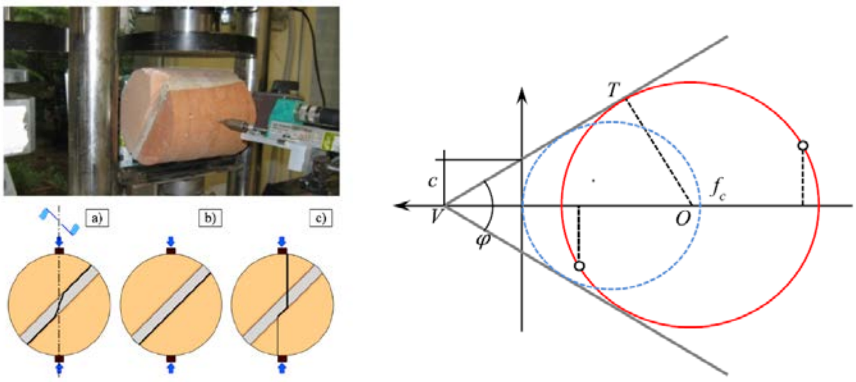


Fig. 17: Stages of flat jack test (Gregorczyk, 2000)

4.4.11. Dynamic structural Monitoring

These methods are based on receiving the information from the behavior of a structure under an excitation induced by a source. Dynamic methods (frequencies, mode shapes and modal damping) compared to static ones (strain or stress) are more sensitive to changes either sudden or gradual change that are caused by damaged, but they need control of environmental and operational factors in order to obtain an accurate result. Instruments in this field could be based on frequency, mode shape or vibration. Tools which act based on frequency are more accurate than those working based on mode shapes, moreover the vibration-based instruments are more recent. On the other hand static methods are simpler since they need only stiffness matrix compared to dynamic ones which require stiffness, mass and damping matrices and the errors compared to dynamic ones are negligible.

4.5. Reinforcement Techniques

Based on the condition of buildings, foundation and soil, the most suitable reinforcement technique should be selected. In the case of historical bridges and in general historical monuments, the interventions should be in accordance with restoration charts considering the age and the value of these types of buildings. Monitoring techniques help to understand the cause of subsidence, scale of the damages and the ground condition. In the meanwhile, since the bearing capacity of the soil has decreased due to the extraction of water, even if the groundwater level rises, there is no precise prediction of the time that the soil regains its bearing capacity and therefore structural and substructural improvements should be considered as well as monitoring surveys in order to decrease the risk of newer subsidence effects. Although there many techniques are available, the particular situation of the bridges of Isfahan permits a limited choice of methods that are discussed in the following subsections.

4.6. Structural and Substructural Interventions

4.6.1. Grouting

Grouting is used to fill the void and in the use of this technique the bond between the grout and the existing material should be considered so that the efficiency of the full section (grout combined with existing material) is guaranteed. The role of grouting is not supposed to increase the loading capacity but it can prevent further deteriorations. The compatibility of the material for grout should be considered in order to make the intervention durable. An aspect that has to be considered is the combination of compressive, flexural and tensile bond of the whole masonry since they can be affected by the properties of the material used in this technique. Most of the historic bridges, including those in Isfahan, are built with hydraulic lime mortar. Several experiments done in this field have proved that lime mortars in comparison to artificial cements are more compatible with most masonry materials.

4.6.2. Repointing

This technique is mainly categorized under the maintenance category rather than repairing. The efficiency of the structure increases by this method but the loading capacity is not affected, besides this method if done in a proper way could prevent deterioration.

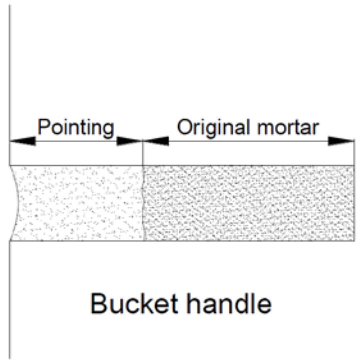


Figure 4-30: Repointing Scheme

4.6.3. Injection

Injection can increase the loading capacity by improving the distribution of loads. The mortar used in this method should also fulfill the compatibility criteria with the existing masonry. Since this technic is difficult to remove thus the status of the building should be analyzed to study the efficiency of this method.

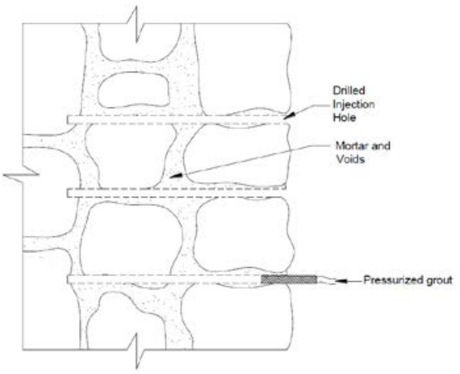


Figure 4-31: Injection Scheme

4.6.4. Replacing Units

Often the concentration of stresses in a specific region could result in the detachment of parts of the masonry. One of the solution to this stands in replacing the part affected that requires a careful consideration of the way in which the new built part is connected to the pre-existing one.

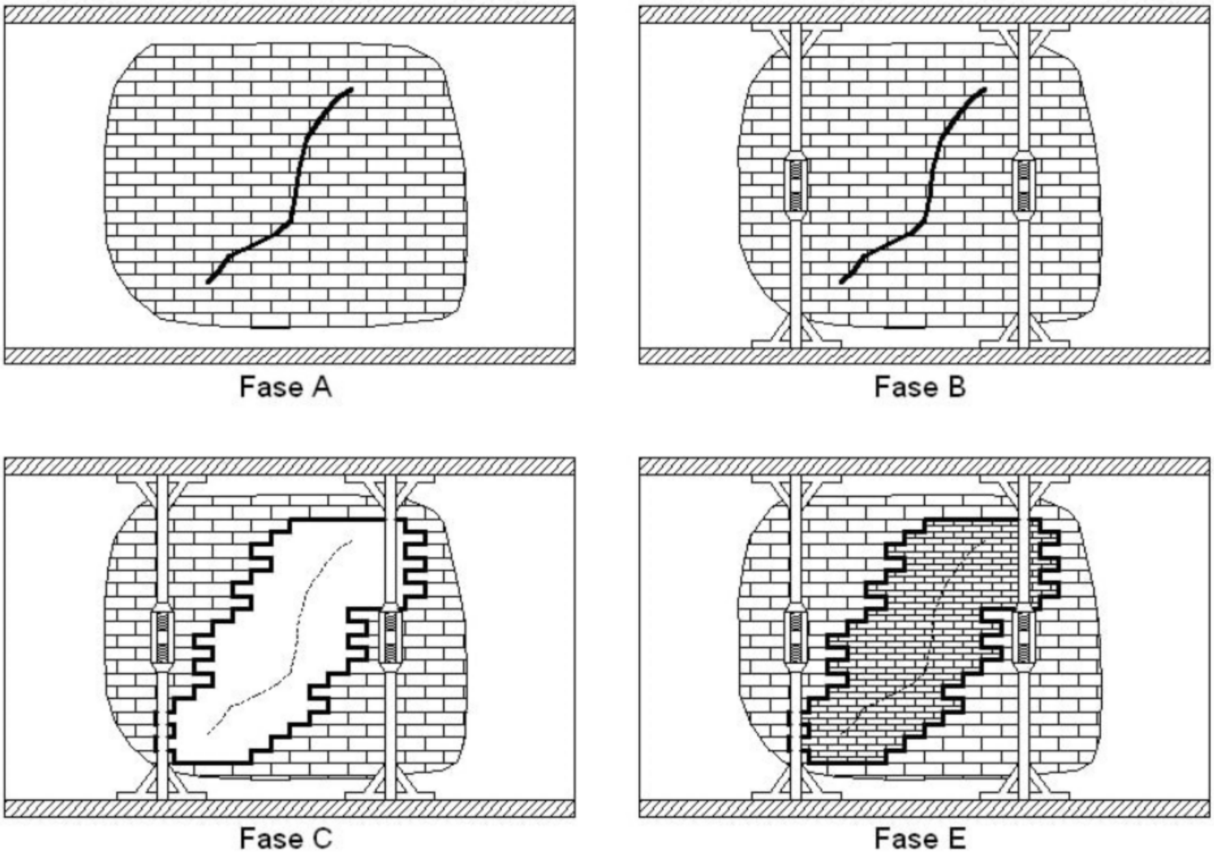


Figure 4-32: Replacing Units

4.6.5. Micro-Piling

Although micro-piling for a historical building could be considered as a heavy intervention, this method is used for the case of settlement as it can provide stabilization for the foundation since they can penetrate through the soil and reach to bedrocks.

4.7. Suggestions

In the city of Isfahan due to stop of the flow of water in the river basin, subsidence has become a very important danger, affecting all kinds of buildings. According to some reports the level of ground water tables has decreased to one third compared to its general situation with data going back to 70 years ago. The consequences of this process are unpredictable considering the existing data and the uncontrollable misuse of the Zayanderood water from its main sources. This might have several negative effects in the near to medium future. Therefore, before reaching a state of decay that is irreparable, actions should be undertaken in regard to the groundwater level in order to prevent possible damages for the structures. As the first step, as proposed in this thesis, it is also essential to gather a thorough and complete understanding of the state of the problem for every structure in relationship to all factors that can potentially impact the bridges. What is suggested is a range of monitoring techniques that can help to collect and systematize data on different structures and in a certain time frame so that data can also be compared.

Based on a study by Hajian Nejad et al. (HajianNejad et al, 2009) some approaches to prevent or decrease the lowering of groundwater level and therefore subsidence are:

- Extraction from groundwater tables should be restricted and managed, or at least should not exceed its current state so that the tables could revive themselves.
- Improvement of water consumption management, considering priorities.
- Use of new technologies to optimize the consumption of water especially in the sector of agriculture.
- Devising techniques to use floodwater for even feeding groundwater tables.

In another study by Shujun et al. (Shujun et al., 2016), the importance of monitoring has been mentioned in the process of mitigating the land subsidence hazard which should be done before the preventive measures. As it is explained in Shujum study, a combination of GPS, InSAR and extensometers were used as monitoring techniques, to check land subsidence in the Yangtze delta. This work indicated that the Levelling technique is one of the common methods to monitor the phenomenon of subsidence in China. For example, in Shanghai, leveling has been continuously used since 1961. Extensometer, GPS and InSAR are also being used relatively since 1965, 1190s and 2003. Moreover, as also reported, the reduction of water as well as the artificial recharge of aquifers, were implemented by the government. For example, in the city of Shanghai, these preventive actions have resulted in a subsidence rate of 5.5mm/year, following an increase in the water table levels in the studied areas. although it has not been mentioned exactly how much was the rate before the undertaken measures, it seems that these measures has decreased the rate of land subsidence which is never equal to zero.

Considering these experiences, one of the main suggestions is to develop a program and plant which involves not only the area near the river but at the scale of the city and the including the regions that are involved in the problem. This study should be done not only as an academic project, but as a nationaly managed one, with a series of policies defined by the government. An important action in Iran, would be to reestablish a correct water flow for the river that could reach all the cities that has been historically connected to the Zayanderood. Meanwhile, using all the available resources to obtain information about the structure of bridges like the Khaju bridge, should be done so as to provide a complete structural analysis of this kind of structures that can fournish a realistic picture of their structural damages and their evolution.

5. A Vision for Enhancing the Role of the Bridge

5.1. Introduction

In order to develop plans for management and preservation of the historical bridges like the Khaju bridge it is necessary to remind how bridges have to be considered important elements of the city of Isfahan that have also shaped its life through time. This should be done considering the contemporary social and economic needs, but at the same time, considering the potential of these monumental structures considering their social and symbolic role in the urban landscape.

The aim of this chapter is to observe how the bridges worked historically as a system. The reason why it is important to discuss this matter is that even if technical structural issues explained in the previous sections are very important for the safeguarding of historical structures, is that these issues cannot be separated from other social and urban aspects. Considering that these aspects are interconnected, addressing them together with the structural ones could benefit the long-term "stability" of the bridges as integral parts of the city. In the following subsections is presented a brief explanation of the history of these bridges with a final discussion on the bridges system in Isfahan, a perspective that is necessary not to just consider them as individual entities.

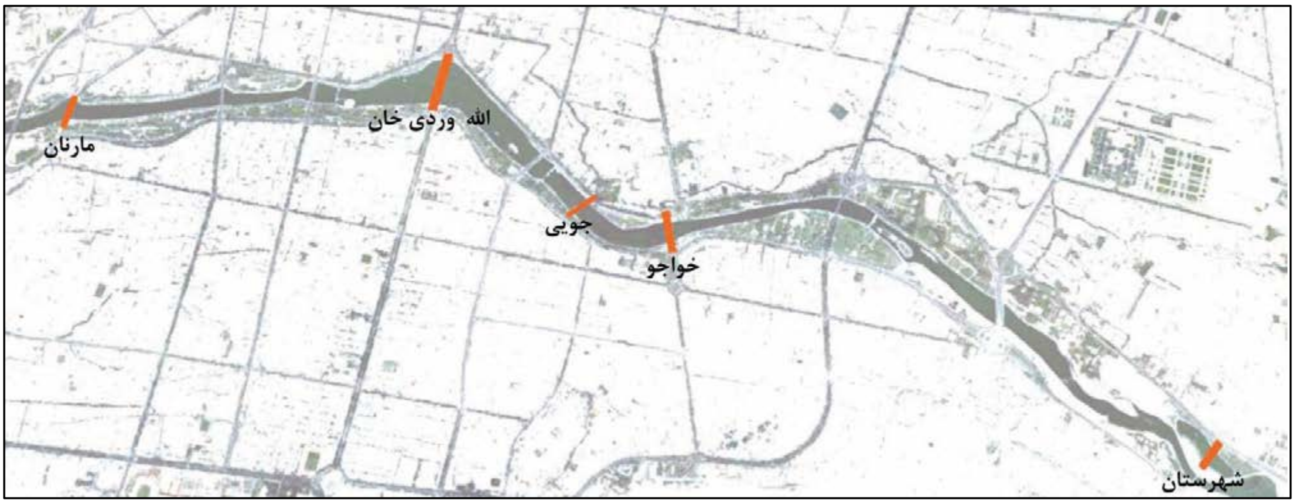


Figure 5-1: The Location of Bridges on Zayanderood (Moravej Torbati and Poor Naderi, 2013)

5.2 The Historic Context of Bridges

5.1.1. Shahrestan Bridge

Shahrestan Bridge is the only bridge of the existing historical bridges in the city of Isfahan which dates back to before Safavid period, and according to some studies it belongs to Sassanid period and until Siljuq period it has been the only important bridge of the city. The bridge acted as a connecting port with southern cities and villages and according to studies, for this reason it includes also a checking point on the northern part.

Figure 5-2: Shahristan Bridge Downstream view with goatherds and flocks in foreground by Robert Byron (Source: Negarestan.ir)

Figure 5-3: Contemporary View of Shahrestan Bridge with the Existence of Water (Source: Tripadvisor)

5.1.2. Marnan Bridge

Is the oldest bridge after Shahrestan bridge and was built in Safavid period mainly to facilitate the commute of people in Jolfa neighbor to Isfahan.

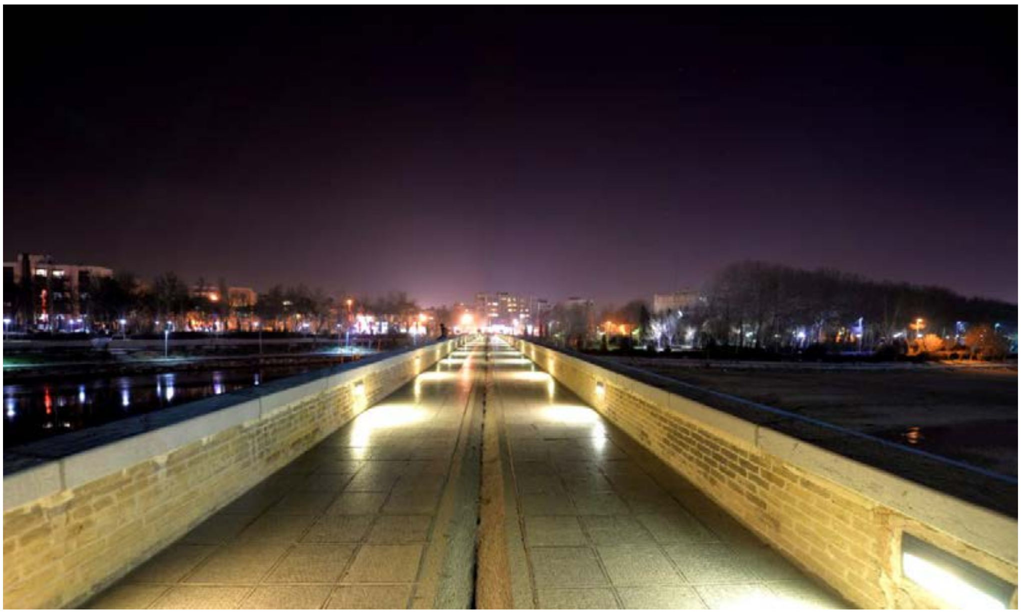


Figure 5-4: Marnan Bridge at Night

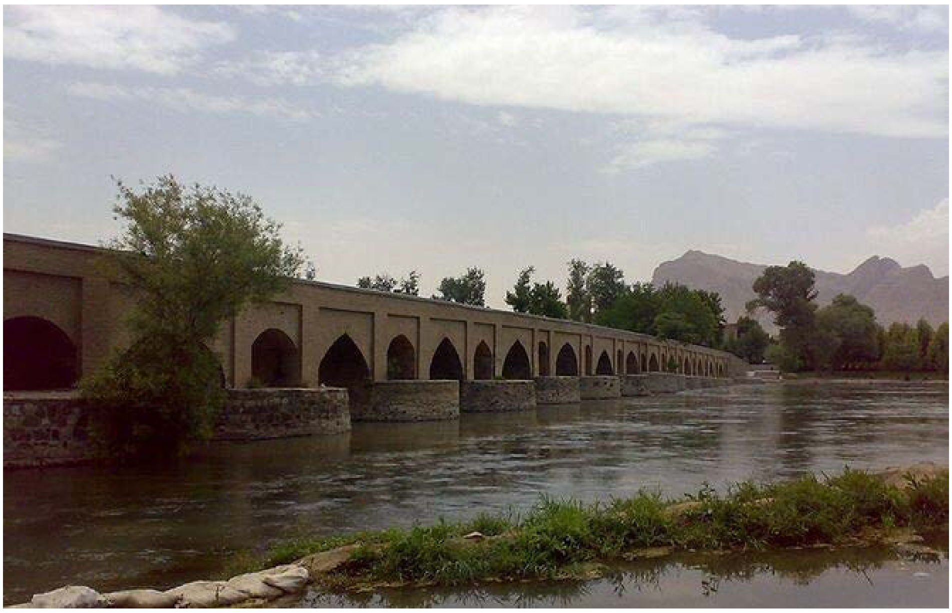


Figure 5-5: View of Marnan Bridge with the Existence of Water

Figure 5-6: Overflow of Zayanderood and Marnan Bridge in November 1954

5.1.3. Si-o-Se-Pol Bridge

This bridge was built in Safavid period, and had a water mill on its upper stream side as well as a waterfall on the northern side, from which there are no left traces at present time. This functions were more diverse on this bridge including a place on the bridge which dominates on the river which was supposed to be a place for the king to participate in specific ceremonies and watch them (with a small pool in the middle and stone benches on the sides), two drinking fountains at both ends of the bridge, and spaces on the ground floor between.

Figure 5-7: Si-o-Se-Pol Bridge,

Figure 5-8: View of Si-o-Se-Pol Bridge

5.1.4. Juei Bridge

This bridge was used as a private bridge for the family of the king and special guests, from specific features of the bridge, the small aqueduct in the middle could be mentioned.

Figure 5-9: View of Juei Bridge

5.1.5. Khaju Bridge

This bridge was built mainly to replace an older bridge and was specifically meant to show the development and advancement of the time. Like Si-o-Se-Pol bridge, in this bridge on its southern and northern parts, the garden streets are built with this difference that one of the existing street gardens on the southern side was built in the Qajar period (after Safavid). One of the important features of the bridge is the small eight-sided palace which was basically a place for the stay and entertainment and was a copy of big palaces.

Figure 5-10: View of Khaju Bridge

Figure 5-11: Details of Khaju Bridge

5.2 The existing perception of the Bridges in Isfahan

The bridges in Isfahan have been considered already for some centuries monuments that shape the collective memory of the people, and partly constitute identity symbols of Isfahan.

Bridges are important connection elements between parts of a city, and the historical bridges in Isfahan that are not open to vehicular access, give people on foot the possiblity to walk and enjoy them as monumental and aesthetically pleasing connection tools. In the current urban texture there are several interruptions that do not allow people on foot to follow a continuous path or route using the historical bridges in order to pass from one side of the city to the other.This issue related to the urban texture and its mobility has a negative effect on the bridges as proper connecting elements, which also affects the people's perception on one of their main functional roles.

An important social place is nowadays constituted not by the bridges, but by the linear park along the river banks, which is still working by linking bridges between them.

The bridges of Isfahan, as well as certain areas like the linear parks connected to them are perceived as a system rather than separate locations, meaning that anything that is done with each of them should be considered in connection to the other elements.

5.3 Suggestions

Having mentioned some historical aspects of the bridges, respecting the chronology of their construction makes us reflect on one of their most important roles which was to connect different urban areas as well rural ones like villages, or neighbors inside the city. The role of pedestrians has always been very crucial considering that ceremonies and other social activities were held near the river in many occasions.

Even if the bridges should be considered a systems in the city, nowadays they are more commonly perceived as single elements, considering all the transformations that has taken place in the city and the urban alterations especially much after their original period of construction. Their important historical connecting function is mostly lost today, as they lie on the dry river as abandoned monument lacking a real function. Possibly, the function of connecting different neighbors could be revived by continuous pedestrian ways that emphasize the connection role of these structures. This issue has been mentioned since at this present moment in time, people visiting historical bridges are mostly tourists, and fewer local people access the bridge to just find a moment of peace, or in a pause without participating in a specific event. The parks along the river seem to be the only place used for walking that are preferred by the inhabitants in all occasions.

Talking about the specific case of Khaju bridge, and having in mind that traditionally, people sing and dance near but especially even under the arches of the bridge, it would be advisable to devise plans that could improve and strengthen these social features..

Considering that the Iranian society is facing big changes and seeing the effort people are making to regain freedom in this very moment of time, it is also important to pay attention to the loss of social spaces, especially when people are increasingly reising their voices against forms of social repression. From these issues, bothering especially women near the river for the case of Hijab, preventing people from dancing and singing and having fun, and other issues that should be remained in the memory of a city so that once they are gained, they are treasured and not allowed to be lost easily. The consideration of these issues along with the structural ones may seem not to have important physical outcomes. Nevertheless, they should be considered for the safeguarding not only of the material objects that constitute important monuments for the city, but also because of the intangible role that certain architectures play for a society and its overall future.

6. Conclusion

As explained in this study the river of Isfahan is experiencing long periods of drought and it is confirmed that the main reason is the loss of balance between input and output of the water from the river system. This imbalance is mainly caused by human interventions, often illegal, and an excessive extraction of water that also takes place in several areas by means of pumping from underground. Having said that, water management policies should be put in place as soon as possible, based on scientific studies and data that should be gain in a systematic and interregional manner. In the current situation of the country, these policies should be considered as a political stance, therefore having little possibility to be implemented as envisioned in this study. Although the current government has not shown any concern about environmental issues, for example the return of water to the river through Isfahan, there is still hope that once the situation changes for better, this type of issue could be promptly addressed, hoping that it will not be too late.

The consequences of the problems of unequal settlements in the ground on buildings and especially on historic buildings should be seriously considered, even if their progress seems to have a slow pace. To stop or prevent the development of cracks or other structural anomalies is to prevent the excessive mismanagement and waste of the water. In the meantime, the affected regions should be monitored and observed to gain information about the geotechnical condition of the area. Meanwhile, the structure of the bridges should be also studied and monitored so that this analysis could be employed to create careful structural models.. Considering that a study on the structural condition of the Khaju bridge was not found in the literature review, one of the suggestions for further research would be to develop a complete structural analysis of the structure, taking into account the effects of settlement. Moreover, while these studies are carried out, it would be advisable to intervene on the stabilization of the structure in order not to expose it to more damages. This is necessary since the resistance of the soil has been compromised due to the excessive extraction of water.

For each step, two aspects have been observed, structure, and substructure, since the technical part concerning the problem affects both the building and its connection interaction with the soil.

In this study, based on the situation of the bridge and its problems related to subsidence, a selection of the most suitable available techniques was suggested. For the monitoring technics, these methods are preferrable:

- Spitir Levelling
- InSAR
- CGPS
- Extensometr
- Piezometer

Besides, for the monitoring of the structure the techniques could be as follows:

- Crack width and tilt sensors
- Infra-red thermography
- GPR

It is important to say that the suggested can be combined together.

For the reinforcing techniques the following methods (for noth structure and substructure) are proposed. They should be chosen depending on a detailed assessment of the particular condition of each bridge.

- Grouting
- Repointing
- Injection
- Replacing Units
- Micro-Piling

Moreover, the vision and plan that takes into account the social and urban role of the bridge (which is also affected by the drought) should be considered as an inseparable aspect from the material and structural stability of the monument. Therefore, stability of the bridge is an important issue which also have affects its social perception. Among the social and urban features linked to the bridge are:

- The connecting function between neighborhoods
- The use of the spaces along the river and bridge in order to involve people more inside the city rather than only providing a place for walking or sitting,
- considering all the things that are changing in the society including the role of women and their freedom for all groups of the society even inside the city.

7. References

- Ahmadi, Reza, Nader Fathianpour. “Using Ground Penetration Radar method for Geotechnical Study of Si-o-Se-Pol Historic Bridge.” *Scientific Quarterly Journal of Iranian Association of Engineering Geology* 9, no. 1 and 2 (2016): 85-102.
- Alizadeh, Hasan, Mohammad Khalaj. “Evaluation of the Physical Development of Isfahan City Based on the Earthquake Risk Analysis.” *Journal of Physical Development Planning 5*, no.2 (Summer 2020): 97-110.
- Ashrafi, Parisa, Kaveh Ostad-Ali-Askari, Amirhossein Ashrafi, Abdollah Jabal-Ameli, Saeid Eslamien. “Investigation of Changes in the Structure of Isfahan City in Ancient Texture, Iran.” *American Journal of Engineering and Applied Sciences*, 2020.
  https://10.3844/ajeassp.2020.204.223
- Benedetti, Andrea, Micro Tarozzi. “Interpretation Formulas for In Situ Characterization of Mortar Strength.” *Construction and Building Materials*, no. 242 (May 2020).
  https://doi.org/10.1016/j.conbuildmat.2020.118093
- Bergamo, Otello, Giuseppe Campione, Stefano Donadello, Gaetano Russo, “*In-situ NDT Testing Procedure as an Integral Part of Failure Analysis of Historical Masonry Arch Bridges*.” Engineering Failure Analysis 57, (2015): 31-55.
- Binda, l., C. Maierhofer, “Strategies for the Assessment of Historic Masonry Structures”, *In In-situ Evaluation of Historic Wood and Masonry Structures*, edited by B. Kasal, R. Anthony and M. Drdacky. Prague, RILEM/NSF Workshop, 2006.
- Building and Housing Research Center – PN 253. I*ranian code of practice for seismic resistant design of building (Iran national Standard No. 2800).* Iranian building codes and standards, 4th revision, 2015 (in Persian).
- Cantini, L. “The Diagnostic Investigations Plan for Historic Masonry Buildings: The Role of Sonic Tests and Other Minor Destructive Techniques.” *In Brick and Block Masonry- Trends, Innovation and Challenges*, edited by Modena, da Porto & Valluzi. London: Taylor & Francis Group, 2016.

- Ferretti, Alessandro, Andrea Monti-Guarnieri, Claudio Prati, Fabio Rocca, and Didier Massonnet. *InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation*. The Netherlands: European Space Agency, 2007.
- Gagliardi, Valerio, Luca Bianchini Ciampoli, Fabrizio D'Amico, Amir M. Alani, Fabio Tosti, Andrea Benedetto, "Remote Sensing Measurements for the Structural Monitoring of Historical Masonry Bridges." *Lecture Notes in Civil Engineering* 200, (2022).
- Gambelati, Giuseppe, Pietro Teatinin. *Land Subsidence and Its Mitigation*. Ontario: Groundwater Project, 2012.
- Ghasemi, Mohammad. "How Zayande-Rud Dried/ When Manifold Management Dried Zayande-Rud". *Mehr News*, August 14, 2014. mehrnews.com/xqYnY
- Ghasemzadeh, Behnam, Moosa Pazhuhan, Hossein Hataminezhad, Hassan Sajadzadeh. " The effect of the Dtrought of Zayanderood on the Social Interaction and Public Spaces in Isfahan." *Journal of Environmental Studies* 40, no.2 (Summer 2014): 481-498. (in Persian)

  10.22059/JES.2014.51214
- Goorabi, Abolghasem, Mostafa Karimi, Mojtaba Yamani, Daniele Prissin. " Landsubsidence in Isfahan Metropolitan and Its Relatioship with Geological and Geomorphological Settings Revealed by Sentinel-1A InSAR Observation." Journal of Arid Environment, no. 181 (2020):

  https://doi.org/10.1016/j.jaridenv.2020.104238
- Gregorczyk, Pawel, Paulo B. Lourenco, "A Review on Flat-Jack Testing." *Engenharia Civil.UM*, No. 9 (2000).
- Hajian, Nasir, Pouria Hajian. *The database of Zayanderood*. Elm Afarin, 2015.
- Hajian Nezhad, Mehdi, Mahmood Hashemi, Mehrdad Hejazi. "Drought, A Thread for the Bridges on Zayanderood." *Danesh Nama*, no. 174-175 (2009): 90-107. (in Persian)
- Hanaei, Ghazaleh, Darab Diba, Hamed Abedini, Masoumeh Yavari. "The Social Impact of the Architectural Components of Safavid Bridges in Isfahan (Case Study:

Kahju And Allahverdi Khan Bridges)”. *International Journal of Architecture and Urban Development* 11, No. 1, (Winter 2021).

- Hashemidehaghi, Sogol. “Study if Inhabited Bridges of Isfahan”. Tesi di Laurea, Universita degli Studi di Padova, 2019.
- Hernández-Madrigal, V., J. Muñiz-Jáuregui, V. Garduño-Monroy, N. Flores-Lázaro, S. Figueroa-Miranda. “Depreciation factor equation to evaluate the economic losses from ground failure due to subsidence related to groundwater withdrawal.” *Natural Science*, no.6 (2014): 108-113.

  10.4236/ns.2014.63015.
- Hosseini Abri, Seyyed Hassan, “Zayanderood and Isfahan.”, *Geographical Researches* 18, no. 3 (2003): 105-118 (in persian).
- Jafari, Reza, Leila Bakhshandehmehr. “Quantitative Mapping and Assessment of Environmentally Sensitive Areas to Desertification in Central Iran”. land degradation & development, No. 27, 2016.
- Kazemi, Yaghesh. Atashgha of Isfahan. Isfahan: Cultural Entertainment Organization of Isfahan Municipality, Isfahanology Center and House of Nations, 2006.
- Luschey, Heinz. “The Pul-I Khawju in Isfahan, A Combination of Bridge, Dam and Water Art.” Iran 23 (1985): 143-151.

  https://doi.org/10.2307/4299757
- Manning, Elizabeth, Luis F. Ramos, Francisco M. Fernandes. “Direct Sonic and Ultrasonic Wave Velocity in Masonry Under Compressive Stress.” *9th International Masonry Conference*, University of Minho (2014).
- Moravej Torbati, Khatereh, Hossein Poor Naderi. “Observation of Effective Traditions on the Formation of Khaju Bridge, Based on the Comparative Study of Historical Bridges of Isfahan.” Bagh-e-Nazar, no. 27 (2013): 61-70.
- Namdarian, Ahmad Ali, Mostafa Behzadfar, Somayye Khani. “The Role of the Network of Madi’s on the Development of Spatial Organization of Isfahan from the Beginning until the End of Safavid Period.”, *Journal of Iranian Architecture Studies*, no. 10 (2016): 207-228.
- Or, Dani, Markus Tuller, Jon M. Wraith. Water Potential. *Reference Module in Earth Systems and Environmental Science*, 2022.

- Pelletier, Antoine, Vazkan Andréassian. “An Underground View of Surface Hydrology: What Can Piezometers Tell Us about River Floods and Droughts?” *Comptes Rendus. Géoscience, Online First* (2023): 1-11.
- Pinho, Fernando F.S., Rafael J.G. Serra, Andrea F.L. Saraiva, Valter J.G. Lucio. “Performance of Single and Double Flat Jacks in Stone Masonry Lab Tests.” *Journal of Building Engineering* no. 42 (2021).
- Shahrnews. “What is the Reason of the Drought of Zayanderood?”. November 27, 2021.
  https://shahrnews.ir/fa/news/89673/علت-خشک-شدن-زاینده-رود-چیست
- Sorkhabi, Omid Memarian. “Evaluation of Isfahan City Subsidence Rate Using InSAR and Artificial Intelligence.” KSCE Journal of Civil Engineering (April 2022): 1-8.
- Tajmir Riahi, Zahra, Rassoul Ajalloeian, Mohammad Ali Rahgozar, Homayoun Safaei. “ Earthquake Hazard Zonation of The Isfahan City, Iran.” Electronic Journal of Geotechniqueal Engineering, no. 19 (2014): 7142-7163.
- Sarvari, Hadi, Mansoureh Rakshanifar, Jolanta Tamošaitiene, Daniel W.M. Chan, Michael Beer. “A Risk Based Approach to Evaluating the Impacts of Zayanderood Drought on Sustainable Development Indicators of Riverside Urban in Isfahan-Iran.” Sustainability, no. 11 (October 2019).

  Sustainability | An Open Access Journal from MDPI
- USGS, Science for a Changing World, “Land Subsidence in California, Measuring and Monitoring,” accessed May 05, 2023, Measuring and Monitoring | U.S. Geological Survey (usgs.gov)
- Yaghmaei, L., S. Soltani, M. Khodagholi, “Bioclimatic Classification of Isfahan Province Using Multivariate Statistical Methods.” *International Journal of Climatology*, no. 29 (2009): 1850–1861.

  DOI: 10.1002/joc.1835
-
-
-