IDENTIFICATION OF VEZİRAĞA AQUEDUCT IN İZMİR AS A HISTORICAL MONUMENT

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by
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"To accomplish great things we must not only act, but also dream; not only plan but also believe."

ABSTRACT

IDENTIFICATION OF VEZİRAĞA AQUEDUCT IN İZMİR AS A HISTORICAL MONUMENT

During 17^{th} century, the developing commercial activities in İzmir took the attentions of senior people from the government to the city. Köprülü Fazıl Ahmet Paşa realized the lack of water supply in İzmir and ordered to construct an aqueduct on Melez valley and fountains to the city center. The system was constructed in 1674 with an aqueduct named Vezirağa Aqueduct, ten old restored fountains and seventy-three new fountains in the city center.

This study aims to identify historical, architectural and structural characteristics of Vezirağa Aqueduct so that its heritage values and conservations problems can be understood.

The geographical and historical characteristics of Vezirağa Aqueduct are described by taking the effects of site and the socio-cultural situation of city into consideration. The architectural characteristics of the aqueduct are prepared by using the site survey datas to reveal the current condition and find out the original state. The original state of the structure explains its historical value and the importance during the construction period. The resistance assesment of the structure is defined by using equivalent static analysis and dynamic analysis by using finite element modeling and time-history analysis.

Finally, the historical, architectural and structural characteristics of Vezirağa Aqueduct prove its historical, documentary and aesthetic values and the structural problems that can damage the aqueduct and affect its values.

ÖZET

İZMİR'DEKİ VEZİRAĞA SU KEMERİNİN TARİHİ BİR ANIT OLARAK TANIMLANMASI

17. yüzyıl boyunca, İzmir'de gelişen ticari activiteler devletin üst düzey insanlarının ilgisini şehir üzerine toplamıştır. Köprülü Fazıl Ahmet Paşa İzmir'deki su sağlama sistemi eksikliğini farketmiş ve Melez vadisine bir su kemeri, şehir merkezine ise çeşmeler yapılmasını buyurmuştur. Sistem 1674'de Vezirağa Su Kemeri olarak isimlendirilen su kemerini, on eski restore edilmiş çeşmeyi ve yetmiş üç yeni çeşmeyi kapsayacak şekilde inşa edilmiştir.

Bu çalışma Vezirağa Su Kemerinin tarihi değerinin ve koruma problemlerinin anlaşılması için tarihi, mimari ve yapısal özelliklerinin tanımlanmasını amaçlar.

Vezirağa Su Kemerinin tarihi ve coğrafi özellikleri, bölgenin etkileri ve şehrin sosyokültürel yapısı göz önünde bulundurularak açıklanmıştır. Yapının mimari özellikleri bugünkü ve özgün durumunu ortaya koymak için arazi çalışmalarından elde edilen bilgilerle hazırlanmıştır. Yapının özgün durumu inşası sırasındaki önemini ve tarihi değerini açıklar. Yapının olası yüklere karşı direnç değerlendirilmesi eşdeğer statik yöntem ve dinamik analizin, sonlu eleman modellemesi yapılarak ve zaman tanım alanında hesap yöntemi kullanılarak uygulanması ile tanımlanmıştır.

Vezirağa Su Kemerinin tarihi, mimari ve yapısal özellikleri yapının tarihi, belge ve estetik değerlerini ve yapıya zarar verip değerlerini etkileyecek yapısal sorunları ortaya koyar.

To my friend, comrade, confidant

My mom

and all strong women…

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CHAPTER 1

INTRODUCTION

Historical monuments are structures which are constructed to create a point of remembrance of a period, person, or event and make people together under the circumstances of their social and physical needs (RT, The Ministry of Culture and Tourism Supervisory Board, 2005). Aqueduct may be included in the two concepts of historical monuments because it makes its constructer and period remembered by its extraordinary structure while fulfilling the water demand of public.

In order to fulfill the demand of water stone or terra cotta pipes were used in the ancient periods, if the water source was above the water outlet. However, if there were level difference between the source and the water outlet, one or more storeyed aqueducts were built (Anabolu, 2001, p. 22).

The construction of aqueducts dates back to 7^{th} century B.C. to Assyrians. (Giovino, 2007). Until the foundation of public water mains, the aqueducts were used to fulfill the water needs of population in conjunction with fountains and cisterns.

In this context, the historical aqueducts as observable parts of water supply systems should be documented and conserved as historical monuments and historical documents presenting the old techniques of carrying water to settlements.

İzmir is a significant commercial city which has hosted different cultures throughout its history. After its re-establishment at Kadifekale (Mount Pagos) in 4^{th} c BC, today's Kemeraltı, then, juxtaposing the inner port, has been the center at which public buildings were erected. However, lack of potable water around the port was an important problem for the city. Therefore, water conveyance systems were built to fulfill the needs of the city center. People built aqueducts, cisterns, and fountains to carry, store and use clean water. They constructed these structures in connection with each other.

Researches on aqueducts of İzmir are limited. Three sources reviewed within the scope of this study are presented in the below.

Weber, G. (1899) collected the notes about the historical waterlines in İzmir that he took during his travel to İzmir in a book. The book was translated by İlhan Pınar in

2011. Weber documented the architectural characteristics of six waterlines and the cisterns in and around Kadifekale. He provided information on the physical charcateristics of the waterlines, and made some sketches to describe the designs of the aqueducts and connections of the aqueducts. He described the options for carrying water in detail. Furthermore, he drew a map showing the routes of all waterlines in İzmir.

Öziş, Ü. et al. (1999; 2008) described the waterlines in İzmir by discussing the information coming from Weber, G. (1899). This study presented the current condition of the aqueducts and updated the map of Weber.

Laflı (2011) evaluates the historical aqueducts of İzmir as late Antique structures (4^{th} to 7^{th} century AD). He provides old photographs of the Vezirağa Aqueduct and Kızılçullu Aqueduct, presenting their views in the early 20^{th} century. He questions the donor of the case study aqueduct: 'It is asserted that the Köprülü Fazıl Ahmet Paşa ordered its construction in 1674'.

This thesis identifies the architectural and structural characteristics of Vezirağa Aqueduct in İzmir so that a basis for planning of its conservation can be established.

Vezirağa Aqueduct is a standing part of a water supply system that was carrying potable water to the city center. It has some structural problems because of the demolished part in the middle. The documentation of Vezirağa Aqueduct including historical, architectural and structural characteristics should be done to conserve the structure in a proper way. The architectural characteristics should be defined and its significance as a historical monument of the city should be identified.

Vezirağa aqueduct, which is subject to this study, was a part of Vezirağa Waterline which was built in 1674 by Köprülü Fazıl Ahmet Paşa (Ürer, 2013). It was constructed on Green Brook in Melez Valley in Buca to carry waters of Kozağaç Brook to ten old and seventy-three contemporary fountains of its era (Ürer, 2013). The aqueduct is in three parts today. Three arches at the top, three arches at the bottom and half of four arches at the center of the aqueduct have been lost today. There is a highway at north and a railway at south passing under and close to the aqueduct. There is also earthquake problem threathening the aqueduct because İzmir is in first degree earthquake zone and experienced destructive earthquakes in the past.

In order to plan its conservation, the characteristics of the aqueduct should be identified heedfully.

1.1. Aim of the Study

The aim of this study is to document the Vezirağa Aqueduct, analyse its architectural and structural characteristics, evaluate its historical significance, and determine its heritage values and conservation problems.

1.2. Content and Methodology

In order to understand the condition of the case study, techniques of architectural restoration and structural engineering are combined. The details of this combined methodology are presented in the below in relation with each chapter. The analytical tables providing information on waterstructures in İzmir are formed within the content of this thesis on the basis of numeric data in preliminary studies such as Ülker (1994), Önge (1997), Geyik (2007), and Topçu (2010).

In the first chapter, the case study of this thesis is introduced by defining the aim, method in relation with content and literature review.

In the second chapter, geographical characteristics of the building and close environment is described in detail.

The geographical characteristics are underlined with two subjects; the geographical characteristics of the city and the landscape of the study area and the seismic characteristics. The location, population, climatic conditions, and vegetation of İzmir are stated with latest numbers. The landscape of the study area underlines the architectural and natural elements around the case study and their current condition. The seismic characteristics include the earthquake risk of Turkey and İzmir in general, the numbers of earthquakes that took place in Turkey and İzmir from 1900 recorded by Kandilli Observatory and the historical earthquakes before 1900 which could have damaged İzmir and the study area.

In the third chapter, the aqueduct is identified in detail with all historical, architectural and structural charateristics. The history of Vezirağa Aqueduct and its conservation state are identified in detail to understand the historical value of the aqueduct. The identification is based on measured survey with tacheometric techniques carried out in September 2014 and Summer 2015, and photographic documentation with the aim of description and also of single image rectification. Limited hand measurements are taken as well. The east elevation, west elevation, two sections and a plan have been completed in 1/50 scale in Autocad 2014 (Appendix A and B). The construction technique, material usage, structural failures, and alterations on the aqueduct are identified with the help of photos and site observations. These analyses are made on measured survey drawing by using colors and symbols. The construction technique and material usage analyses are combined, while structural failures and alterations are shown together. In the last part of this chapter, in order to find the lateral load resistance of the aqueduct some mathematical calculations are made. The technique used by Gürel, et al. (2010) is integrated to the aqueduct to obtain the structural resistances of the structure. The calculations are made in Matlab software for Bozdoğan Aqueduct. After the results are checked, the calculations are made with the values of Vezirağa Aqueduct. The aqueduct also is modeled in SolidWorks software in order to find out six modes of the building in Ansys software.

In the fourth chapter of this thesis, historical research is carried out to identify historical water stuructures such as fountains, kiosks (*sebil*), *şadırvans*, cisterns and water conveyance systems in İzmir. The connections between the water structures are defined graphically to show the route of the water in the city. Then, similar aqueducts from Ottoman period (16th, 17th, and 18th centuries) are defined, and comparative study is made with 10 examples. The parameters of comparison are fors, contruction techniques, arch characteristics, and material characteristics. The results are illustrated on tables.

In the fifth chapter, the period analysis and restitution of the aqueduct are presented. The period analysis is made with mapping technique on measured survey drawings by defining six different periods. The historical evaluation describes the importance of Vezirağa aqueduct among Ottoman period water conveyance systems. The restitution illustrates Vezirağa Aqueduct as an Ottoman monumnet in the second half of the 17th century (phase 2). The possible of the existence of a previous aqueduct in the same location has been discussed by various scholars (phase 1), but the restitution of a possible antique structure is beyond the limits of this study. The restitution problems for the 17th century aqueduct are defined, and the restitution solutions are formulated together with their sources and reliability degrees (Appendix G1 and G2).

The sources for the restitution of the aqueduct are defined as the traces coming from the aqueduct itself (Appendix A), old photographs, the written documents, and comparative study within the building. The traces coming from the aqueduct and the old photographs are the most reliable sources. The written information provided by various travellers is takens as a second degree reliable source. Comparative study within the building is third degree reliable source. These four sources are used to examine the existence (E), location (L), form (F), material (M) and detail (D) of the restitution problems.

The reliability degrees have two levels according to the sources of existence, location, form, material and detail of restitution problems. The first level includes exactly known ELFMD with most reliable sources; traces coming from the building and the old photographs. In the aqueduct, the restitution of remains of original arches at the south end of wall portion A and north end of wall portion B, the repaired brick – stone masonry arches on the south end of wall portion A, and the arch on wall portion B are included in this level. The second level has two options for the reliability levels of ELFMD. In the first option, all information comes from written sources. This is seen in the nonexistence of buttresses on wall portion A in this structure. The second option is about having the exact information of ELF from traces coming from building and old photographs, while having the information of M or D, or both from comparative study within the building. In the aqueduct, the second option is observed in the demolished part between wall portions A and B, the demolished stone duct, and restitution of the demolished part on the railway.

In the sixth chapter, historical, architectural and structural evaluations for the aqueduct are presented. According to the results of calculations in the third chapter, the resistances of the aqueduct to the possible death and live loads are defined in detail. The importance of the conservation of the current condition is defined for its historical value. The qualities of the historical monument and its conservation problems are stated.

CHAPTER 2

GEOGRAPHICAL CHARACTERISTICS

Vezirağa Aqueduct, Yeşildere, İzmir is located on Yeşildere Highway connecting Yeşillik Street and Altınyol in between Buca and Konak districts at the southern skirts of Kadifekale. The Yeşildere Street is 4.5 km long, and runs in southwest – northeast direction, parallel to Yeşildere in the Melez valley. The aqueduct crosses the Yeşildere at 2.44 km from Altınyol end. It also crosses the railway which is used by İZBAN today at its south end.

In this section, the geographical characteristics of the site are introduced starting with İzmir city and continuing with the landscape of the case study. Then seismic characteristics in İzmir with an eye on the study area are presented. Finally, historical developments in the study area and evolution of water supply systems with emphasis on those in the study area are presented.

2.1. Geographical Characteristics of İzmir

İzmir is located between 37° 45' and 39° 15' northern latitudes, and 26° 15' and 28° 20' eastern longitudes with 12012 km² surface areas. The population of the İzmir Province was 4,113,072 in 2014. The city has Mediterranean climate which has long, hot and dry summers; and mild to cool, rainy winters. The city consists of 60 % mountainous areas, 18 % plateans and 22 % plains. The vegetation of the city contains 52 % forests, 33 % plantations and 15 % pastures (*mera*). Calabrian pine, umbrella pine, black pine, cypress, lemuroid and olive trees are mostly seen in the flora. In the fauna of the city, bovine and ovine breeding and poultry raising is prevalent. Cattle, sheep, goat and chicken are mostly used to obtain animal origined foods (Eliçalışkan, 2007-2014).

2.2. Landscape of the Study Area

The main geographical components of the studied landscape are the mounts, valley and the brook. Melez Valley is the deepest point in İzmir which is 25 m from sea level (Weber, 1899).

Kadifekale, 186 m in height, crowns the city of İzmir and it is visible from various positions at land.

At the southern skirts of Kadifekale, Meles brook – valley system, 30 m from sea level, is located. Yeşildere feeding the Melez brook runs in north and south directions. Today, Yeşildere is dry. It is bordered by Mount Nif, 1510 m height, at its south. Besides the rocky terrain of the mounts, typical Mediterranean coat is observed.

The south western skirts of Kadifekale are recently forested after the removal of the squatter houses, which had the risk of landslide.

Atatürk Rölyefi (Atatürk Relief) is located on the south east of the Melez valley which was constructed between 2006 and 2009.

Uçan Yol (Homeros) at the northwest of Yeşildere Street and Atatürk Relief was completed in 2013 continuing.

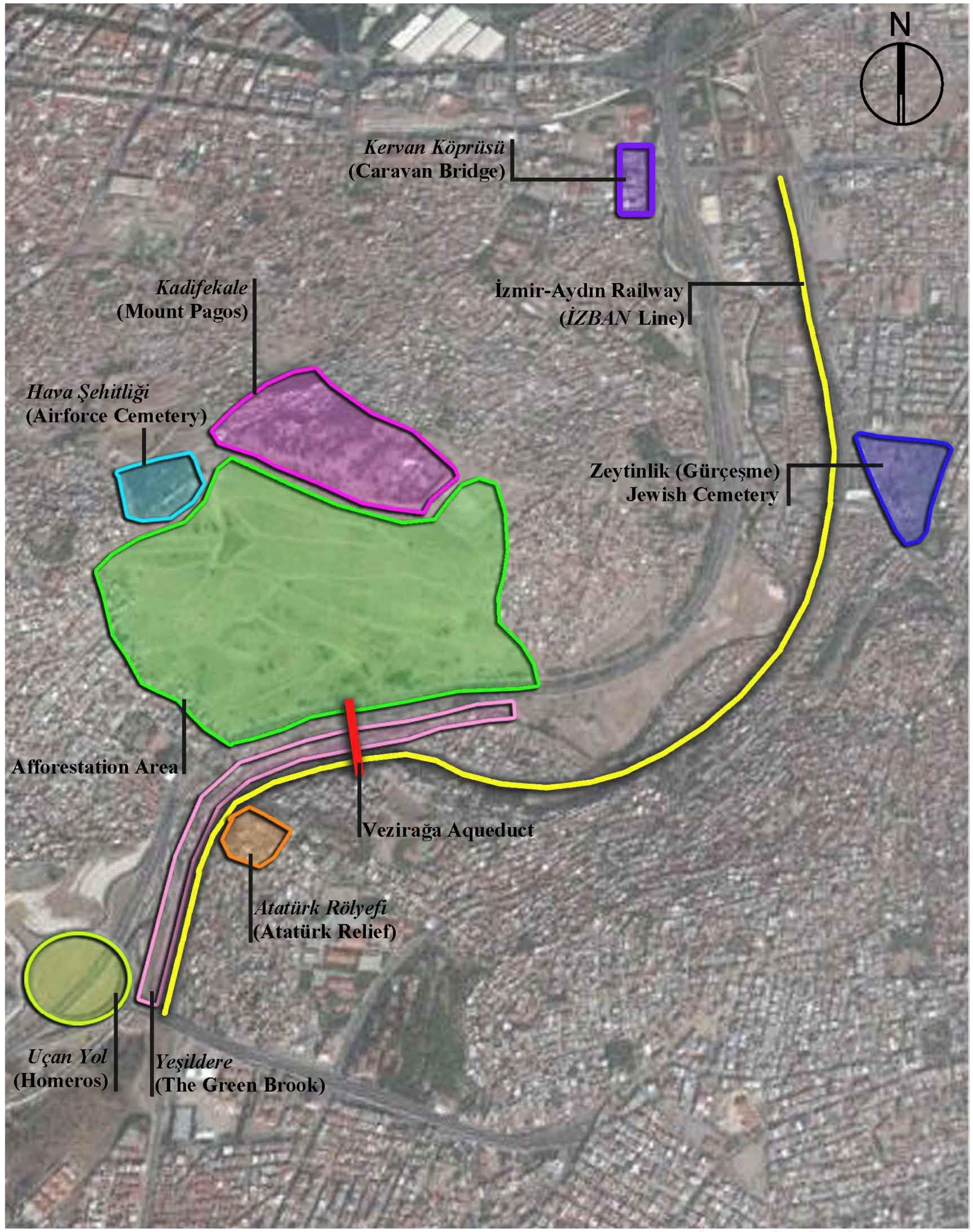
The south of the valley is full of unqualified housing units between the brook and the railway. The area is a squatter settlement with an abandoned tannery and leather factory. 156 tannery and leather factories were demolished in the area in order to improve its urban quality (kentyasam.com, 2002). The nineteenth century İzmir – Aydın railway is located at the end of this squatter area and used by İZBAN today.

The Caravan Bridge which provided link with northern and central Anatolia was located at north east of study area.

Zeytinlik Jewish Cemetery is located at east of aqueduct on Meles valley.

A cemetery special for airman and pilots is another important element for the study area and İzmir close to Kadifekale.

Table 1. The architectural and natural elements around the study area.



The map showing the location of the elements of the study area

Veziråga Aqueduct

Kervan Köprüsü (Caravan Bridge) (Source: Apikam, c2016)

İzmir-Aydın Railway (*İZBAN* Line) (Source: Proje İzmir, 2011)

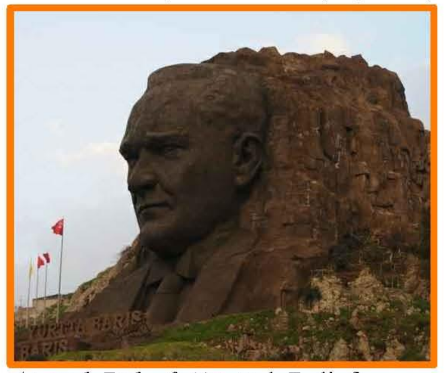
Kadifekale (Mount Pagos) (Source: İzmir Metropolitan Municipality, c2015)

Hava Şehitliği (Airforce Cemetery) (Source: Wikipedia, 2011)

Zeytinlik Jewish Cemetery (Source: İzmir Metropolitan Municipality, c2015)

Uçan Yol (Homeros) (Source: Hürriyet, 2014)

Yeşildere (The Green Brook) (Source: Proje İzmir, 2011)



Atatürk Rölyefi (Atatürk Relief) (Source: İzmir Metropolitan Municipality, c2015)

Afforestation Area (Source: Proje İzmir, 2011)

2.3. Seismic Characteristics

Turkey is on the list of the most dangerous seismic zones in the world. There are five degrees of seismic zones in Turkey; Aegean Region is totally in the first degree zone. Izmir is located on the tectonic laminate of Asia and Africa. Therefore, the earthquake risk in İzmir is quite high (RT, Directorate of Seismic Research, 1996a).

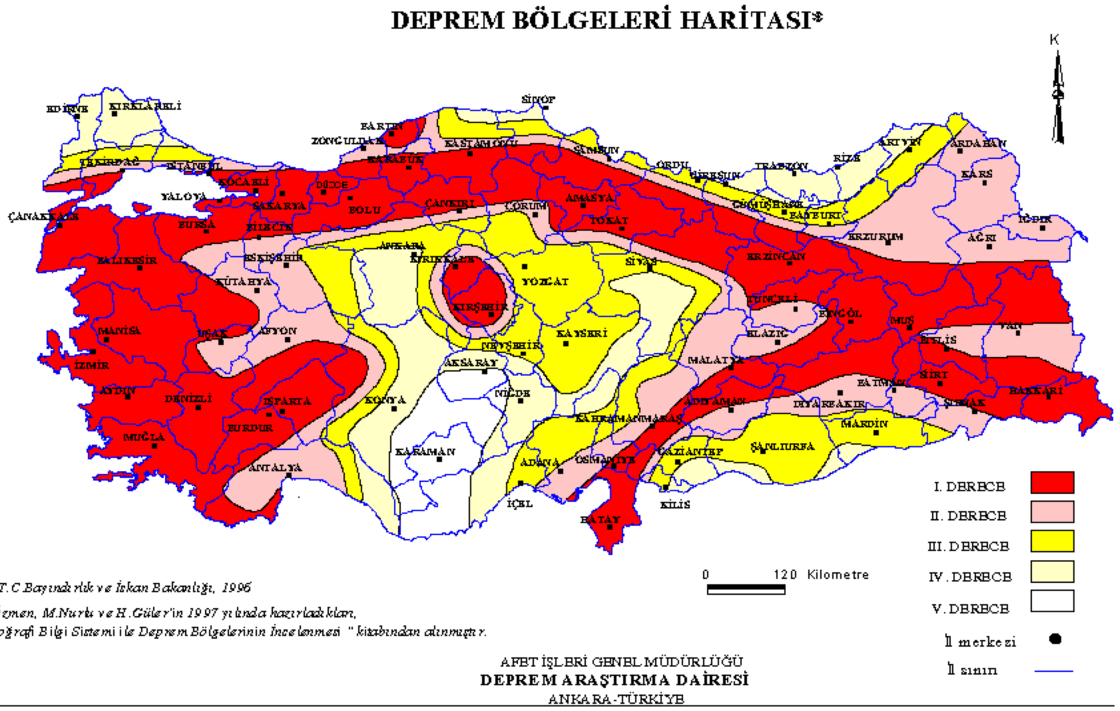


Figure 1. The map of seismics zones in Turkey.
(Source: RT, Directorate of Seismic Research, 1996a)

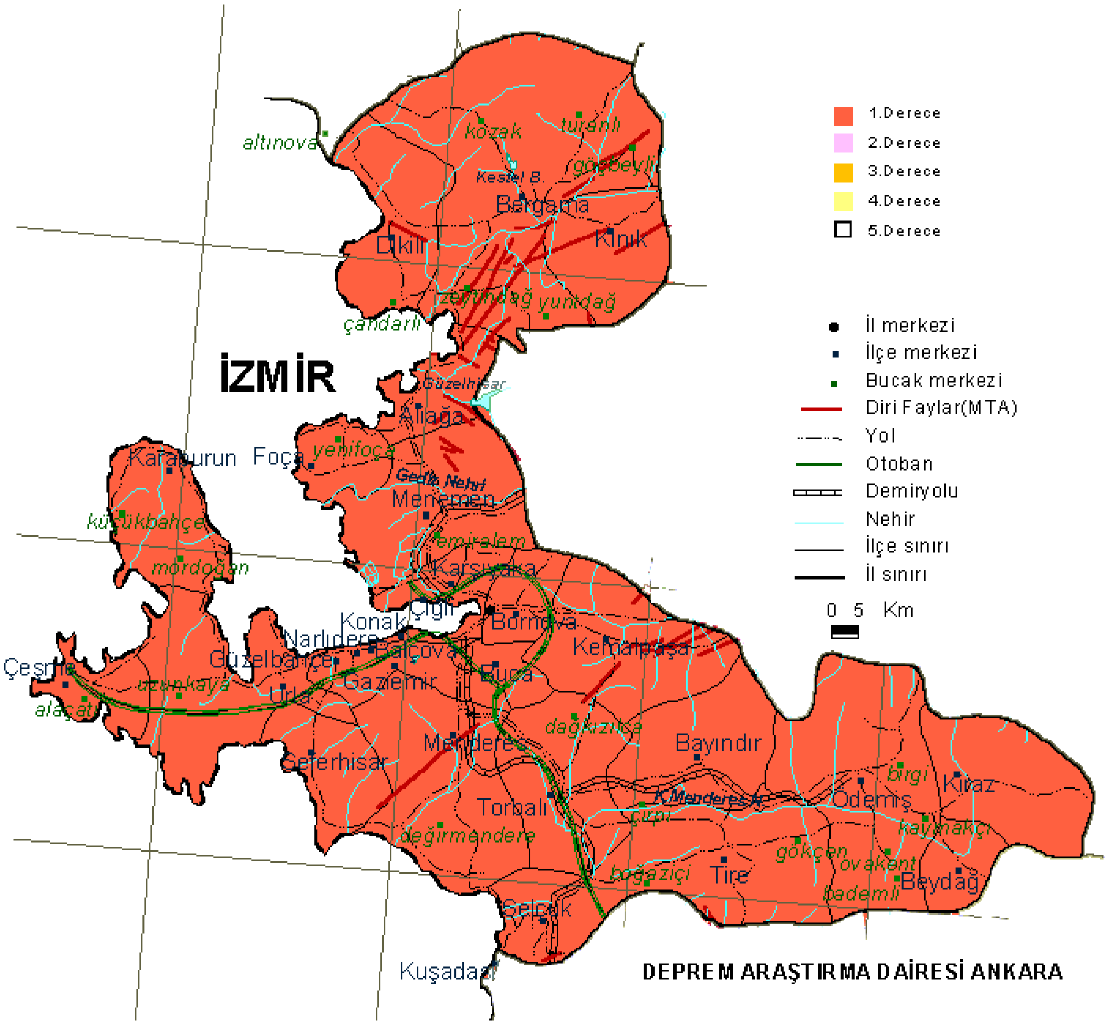


Figure 2. The map of seismicity of İzmir.
(Source: RT, Directorate of Seismic Research, 1996b)

According to the records of Kandilli Observatory, there were 40 important earthquakes in Turkey from 1688 to 1900. Since 1900, Kandilli Observatory records each earthquake. These records show that 182 355 earthquakes took place in Turkey with different magnitudes since 1900 (http://www.koeri.boun.edu.tr/sismo/2/en/).

13 433 of these earthquakes took place in Aegean Region.

2 226 earthquakes have been recorded in İzmir since 1900 (Table 2). None of these were major earthquakes. However, relatively strong ones had caused some damage in the city.

Table 2. Statistics of Earthquakes in İzmir since 1900.
(Source: RT, Directorate of Seismic Research, 2015)

DEFINITION	MAGNITUDE	AVERAGE PER YEAR	İZMİR STATISTICS (SINCE 1900)
Great	8 > =	1	0
Major	7 - 7.9	18	0
Strong	6 - 6.9	120	4
Moderate	5 - 5.9	800	27
Light	4 - 4.9	6200	158
Minor	3 - 3.9	49000	1243
Very Minor	3 <	2.0 - 3.0 = 1000 (per day) 1.0 - 2.0 = 8000 (per day)	794

Thirty strong earthquakes took place in İzmir after the construction of the aqueduct. Their magnitude varied between 4.8 and 6.7. Eight of these historical important earthquakes took place in the city center of İzmir and they should have damaged the aqueduct (Biro, 2000) (Table 3).

The first one took place in 10.07.1688, just after the construction of the aqueduct. This earthquake generally affected the coastline and topography of the city. Over 15.000 people died. Therefore, the addition of the buttresses to the aqueduct may be explained with this event.

During September and October of 1723, there were two earthquakes in the city center and 100 buildings were lost.

In the 4th of April in 1739, another earthquake occurred with 5.8 magnitudes. No fatalities and building losses are recorded.

In the 10th of September in 1904, an earthquake took place with 5.8 magnitudes whose center is very close to the aqueduct. Probably, it was one of the most damaging earthquakes for the aqueduct.

In 01.02.1974, there was another strong earthquake with 5.5 magnitudes. There were 2 deaths and 47 building were lost during this earthquake.

Finally, in 1977, Izmir faced with one of the strongest earthquakes of its history. In one week, there were two earthquakes with 4.8 and 5.5 magnitudes. The buildings lost in this earthquake were forty in number. The center of these earthquakes was close to the aqueduct like the one in 1904.

Table 3. Historical earthqueakes which could have damaged the aqueduct.
(Source: RT, Directorate of Seismic Research, 2015)

DATE	LOCATION	MAG (Ms)	FATALITIES	DAMAGED BUILDINGS
10.07.1688	İzmir	-	15000	Coastline and topography
09.1723 - 10.1723	İzmir	-	500	100
04.04.1739	İzmir	-	-	-
10.10.1904	İzmir	5.8	-	-
01.02.1974	İzmir	5.5	2	47
09.12.1977	İzmir	4.8	-	10
16.12.1977	İzmir	5.5	-	40

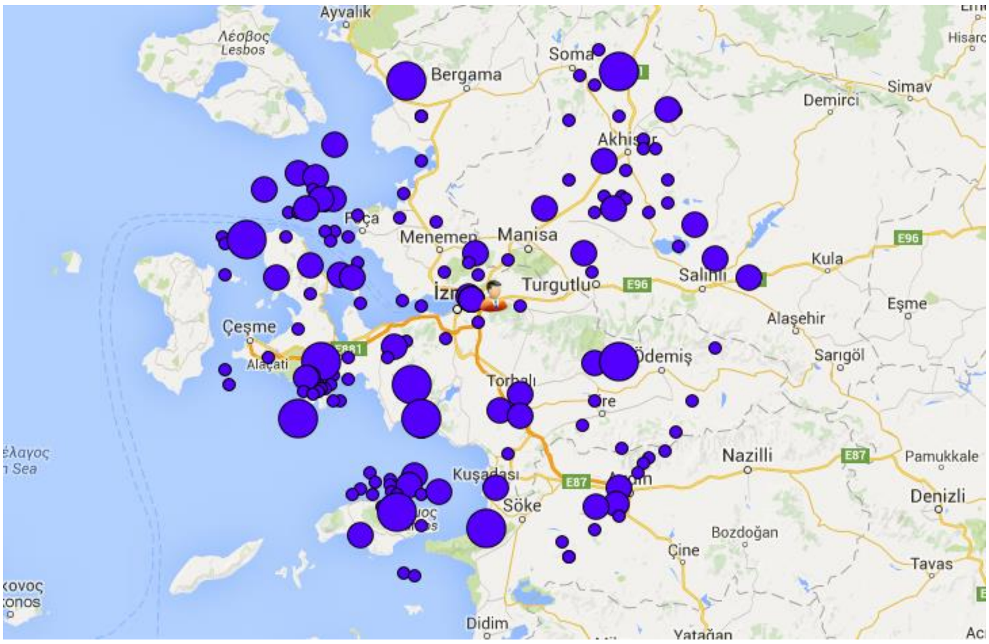


Figure 3. The map of important earthquakes in İzmir and its environment
(1900 – 2010). (Source: Koeri, 2010a)

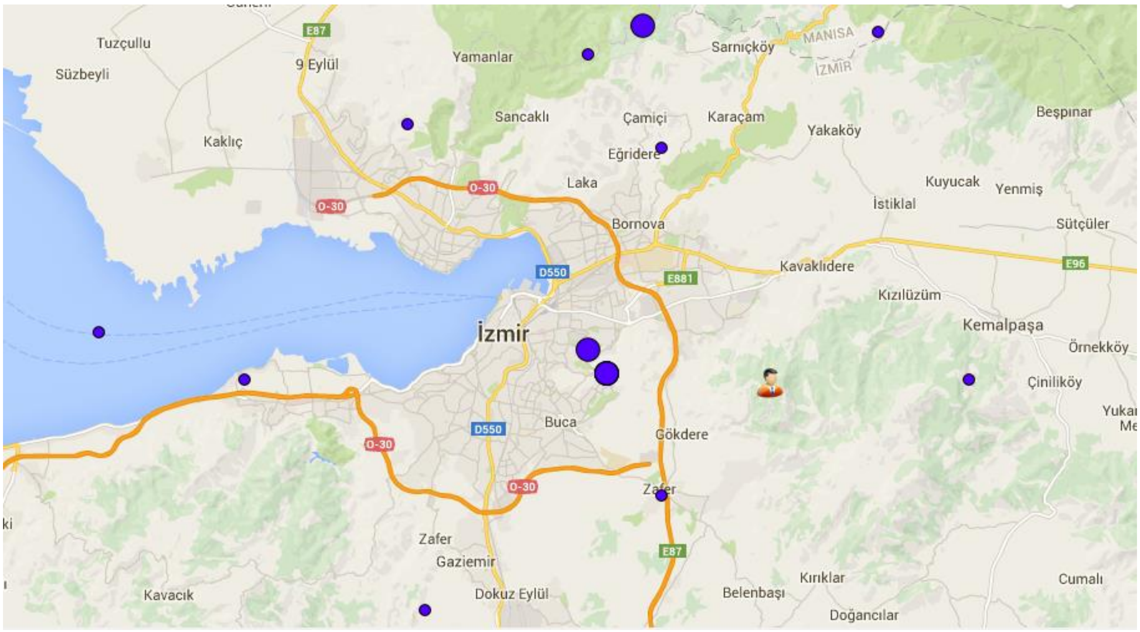


Figure 4. The map of important earthquakes in İzmir center (1900 – 2010).
(Source: Koeri, 2010b)

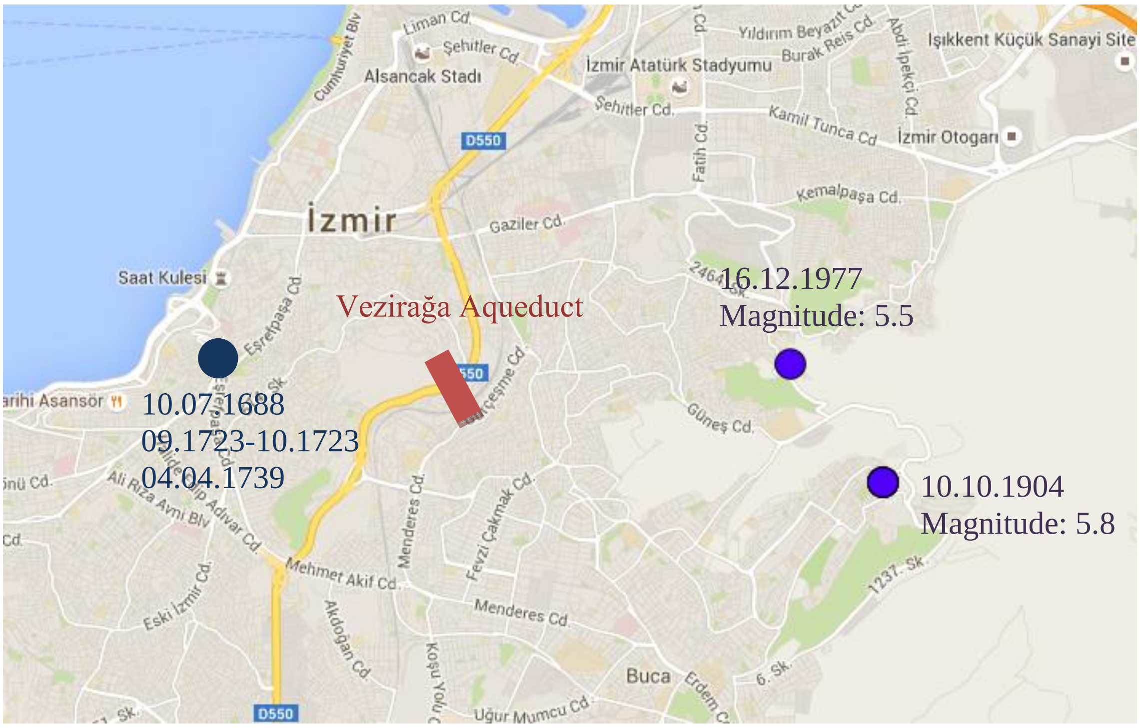


Figure 5. The map of important earthquakes close to the Vezirağa Aqueduct.
(Source: Revised from Koeri, 2010c)

CHAPTER 3

IDENTIFICATION OF THE AQUEDUCT

Vezirağa Aqueduct is on Yeşildere Street in Buca district. In this chapter the general historical, architectural and structural characteristics of aqueduct is identified in detail.

3.1. Historical Characteristics

Vezirağa Waterline is a water conveyance system to carry water from Kozağaç Spring. The waterline has a different building technique compared to the other waterlines around. A duct was built 5 m below ground level in order to collect the underground water in the vicinity. It rises to the surface in three different points, as stated by the locals. One point is 52 m above sea level in Melez valley. The other point is near the mill between the two Ottoman Aqueducts. The last point is on the Paradiso slope.

There were stone pipes waterlines on both sides of Melez Brook which passes the valley with high pressure. These waterlines were damaged during the construction of the aqueduct (Weber, 1899).

Vezirağa Aqueduct was built on this waterline in Melez Valley on Green Brook in Buca. It is claimed that an aqueduct in this location was first built in the 4th century BC firstly. However, the information on the present aqueduct is that it was built by Köprülü Fazıl Ahmet Paşa in 1674. Some travelers (Pococke; Storari) stated that there could be the ruins of the old aqueduct before the 17th century construction. The other important feature of the aqueduct is the construction technique of the bottom levels: it is similar with the old city walls. This similarity shows that there could be an old water supply system in the ancient times (Figure 6). However, Weber does not share this view. He claimed that the stones of the bottom levels are collected from ruins and castle in the city (Weber, 1899). Köprülü Fazıl Ahmet Paşa used the stones of ruins in the construction of khans and restoration of *bedesten* (Aktepe, 1976). Ülker (1994) said that the vizier built a big arched waterline. When all these informations compared, it can be said that the construction date of the aqueduct is 1674.

The aqueduct is the first aqueduct on the Yeşildere street through Buca direction. Because of that, in some sources it was named as “1st Aqueduct” (Figure 24).

The aqueduct is around 165 m in length, 19 m in height and continuous 5 m below the ground level. In the construction rubble stone was used for the duct and arches (Weber, 1899; Ürer, 2013). Devşirme malzeme kullanıldığını belirt. Sayfa 47 ve 22. After its construction, three buttresses on east façade were added to support the aqueduct as seen on Weber’s plan (Figure 6). The arches in the center of aqueduct collapsed in a spate in 1931 (Akyüz Levi, 2009, p. 161). Today the aqueduct is on Yeşildere Street and the three roads of the street are passing through the arches of the aqueduct (Figure 7). One arch of the aqueduct is in between the housing units close to the İzmir – Aydın Railway. These roads and housing units crate problems to protect the Vezirağa Aqueduct which is the only aqueduct with an exact construction date and good condition compared to the others.

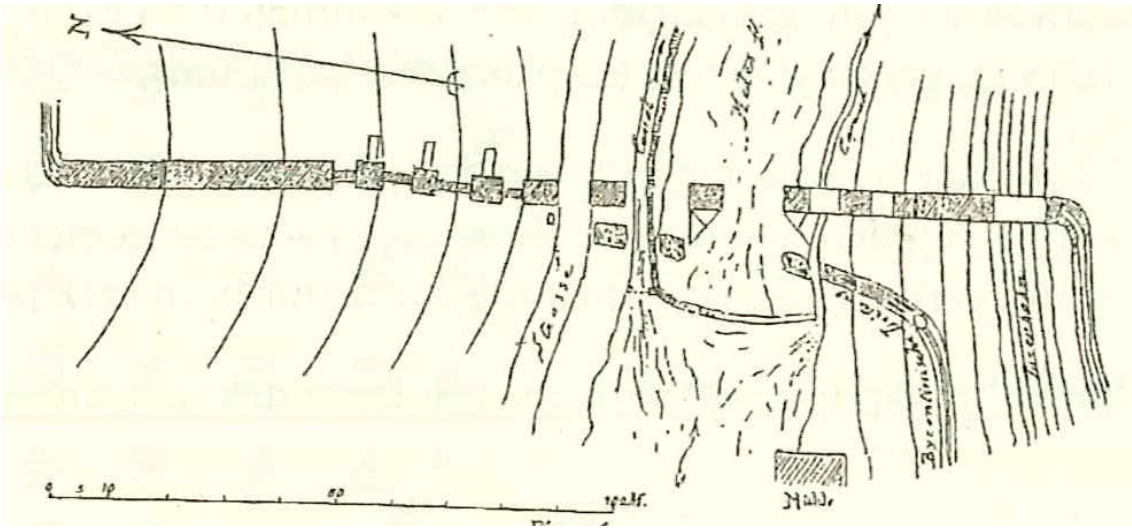


Figure 6. The plan of Weber showing Veziağa Aqueduct.
(Source: Weber, 1899)

Figure 7. Present situation of Veziraĝa Aqueduct.

3.2. Köprülü Fazıl Ahmet Paşa's Architectural Contribution to İzmir

Köprülü Fazıl Ahmet Paşa was born as a member of a strong family in 1635 in Köprü Town in Amasya. His family was in the Ottoman administration for 27 years as viziers. Köprülü Fazıl Ahmet Paşa was vizier for 16 years between 1660 and 1676 until his dead. During his life span as a vizier he conducted lots of architectural activities. Because of the rise of İzmir in the 17th century, he built different public buildings to support development of commerce and improve life quality at the city center (Table 4) (Topçu, 2010).

Table 4. Architectural activities of Köprülü Fazıl Ahmet Paşa in İzmir.

Type of Building	Number	Location	Reachability
Mosque	1	Kasap Hızır Neighborhood	-
Fountain	57/73*	City center	-
Khan	2	Kasap Hızır Neighborhood	-
Shop	93	City center	-
Bath	1	Balık Pazarı	-
Customs House	1	Unknown	-
Aqueduct	1	Melez Valley	+

* In majority of the sources the number of fountains constructed by Köprülü Fazıl Ahmet Paşa is given as 73 (Ülker,1994; Kayın, 2013; Ürer,2013) but Topçu (2010) gives this number as 57.

3.3. Conservation State and Planning Decisions

Vezirağa Aqueduct was registered in 17th January of 1975 with decision number 152 by General Directorate of Antiquities and Museums.

On 10th May of 2007 with the decision numbered 2312, the aqueduct was registered as monument in master plans. This decion included a buffer zone same height with the aqueduct, in order to coordinate the relation of the aqueduct with the housing area at its south. However, the housing units threathening the monument, especially wall portion B, have not been cleaned so far.

Figure 8. Wall portion B with its surrounding

On 5th June of 2007, the explanation of 'Korunması gerekli kültür varlığıdır' was added to master plans.

In 2012, the illumination project of the aqueduct was prepared and it was applied.

3.4. Physical Characteristics

The physical characteristics of the aqueduct are to be presented under two sub-headings as site characteristics and aqueduct characteristics.

3.4.1. Site Characteristics

The aqueduct is located on Yeşildere Highway in Buca district on the south of hill skirts of Kadifekale (Figure 9). The highway runs through the Melez valley in east-west direction. Yeşildere runs through the valley. Its flow/debit is not constant and the brook dries in summers. The structure is in ruins and only its three portions have reached today which are named as wall portion A, B and C in the context of this thesis. The wall portion A leans onto the hill skirts of Kadifekale at the north-south direction. The wall portion B is at the center and on the bed of the brook. The final part, wall portion C, is at the north-south direction and next to the railway, which is used efficiently by İZBAN today.

Figure 9. The location of Vezirağa Aqueduct on Yeşildere Highway.

3.4.2. The Aqueduct Characteristics

The characteristics of the aqueduct are defined under three titles; Layout and Form, Construction Technique and Material Usage; and Structural Failures, Material Deteriorations and Alterations.

3.4.2.1. Layout and Form

In its original design, the Aqueduct is a wall in north-south direction and perforated with a series of arches. It has lost its integrity and only three portions of it have reached today (Appendix B).

The wall portion A (1.70 x 81.30 m) is located on the three bands of the highway (Appendix B). It is a stone masonry wall, perforated with five brick arches and has a duct on its top (Appendix B). The two side walls of the duct are 55 cm in width, the dyke is 60 cm in width. The first, second, third and forth arches are two centered (bicentric) arches. The radial and distance between each bicentric center is 3.3 m, 3.3 m, 3.4 m and 2.1 m; and 1.3 m, 0.9 m, 0.3 m and 0.6 m, respectively. The fifth arch has one center. The first arch is 6.06 m high from the ground level and 3.21 m from the springing line (Appendix B). The span of the arch is 5.1 m. The second arch spans 5.50 m, 9.20 m in height from the ground level and 3.20 m in height from the springing line. The third arch spans 5.30 m, has 8.68 m height from the ground level and 3.20 m in height from the springing line as the first and second arches (Appendix B). The forth arch spans 3.80 m on the top of the fifth arch (Figure 12). The height of the forth arch is 5.20 from its own ground level and 2.10 m from the springing line. The fifth arch spans 3.80 m, 5.36 m in height from the ground level and 0.90 m in height from the springing line. The remains of the sixth arch are seen at the south end of this portion (Figure 13).

Figure 10. West elevation of wall portion A.

Figure 11. East elevation of wall portion A.

Figure 12. The fourth and fifth arches of wall portion A from the north end.

Figure 13. The demolished arches at the south end of wall portion A.

The wall portion B (1.70 x 26.30 m) is a stone masonry wall with the remains of two arches (Appendix B) and a full arch positioned on the stream bed (Appendix B, Figure 14). The side walls of the duct are ~ 63 cm in width, the dyke is 38 cm in width. The radial and distance between each bicentric center is 2.8 m and 0.9 m respectively. The arch on this portion spans 4.80 m, 7.30 m in height from the ground level and 2.90 m in height from the springing line (Appendix B and Figure 15).

Figure 14. West elevation of wall portion B.

Figure 15. East elevation and demolished arches of wall portion B.

The wall portion C (1.70 x1.00 m) is just next to the railway at its south. It rests on the rocky terrain at its north end (Appendix B, Figure 16). This portion is almost in ruins. On this portion, only the traces of the stone duct are seen with 55 m side walls and 60 m dyke. The total height of this portion from the ground level is 5.40 m.

Figure 16. Wall portion C.

3.4.2.2. Construction Technique and Material Usage

The Aqueduct is composed of structural and architectural elements with different construction techniques and materials (Appendix C1).

3.4.2.2.1. Structural Elements

The structural elements are defined under five systems; stone masonry wall system, brick masonry arch system, buttresses, wooden horizontal lintels and iron reinforcement.

3.4.2.2.1.1. Stone Masonry Wall System

The stone masonry wall is composed of three independent portions (length of A: 81.30 m, length of B: 26.30 m, length of C: 1.00 m) in north-south direction on the four-lined highway and the single-lane railway. All portions are composed of rubble stones (~ 20 x 50 cm) and mortar (~2 cm in thickness). The corners are reinforced with cut stone (~ 45 x 85 cm), some antique stones were reused in the composition. The wall is exposed without plastering and paint (Appendix C2 and Figure 11, 14 and 16).

Stone and brick additional masonry wall system at the south of the wall portion A (85 x 325 x 697 cm) is composed of rubble stones (~ 15 x 35 cm), bricks (~ 4 x 12 cm) and mortar (~2 cm in thickness), and exposed without plastering and paint as the rest of the stone masonry wall (Appendix C2 and Figure 12).

3.4.2.2.1.2. Brick Masonry Arch System

A series of arches perforates the wall portion A. These are four original arches, whose spanning distance is ~ 5.50 m and height from springing line to the keystone is ~ 3.20 m. The southern arch is reinforced with additional two arches, positioned in vertical order and with spanning distance of ~ 3.80 m. All arches are composed of bricks (~ 4 x 20 cm) and mortar (~2 cm in thickness), and exposed without plastering and paint. The arch perforating the wall portion B has similar characteristics with the arch series on wall portion A (Appendix C2, Figure 10, 11 and 15).

At the end of wall portion A and B, there are the remains of some other original arches, composed of bricks and mortar and exposed without plastering and paint (Appendix C2, Figure 13 and 14).

Two blind arches are on the east facade of wall portion A 23.80 m and 28 m from the northern end (Appendix C2 and Figure 17). These arches span 1.70 m (r: 88 cm) and 1.40 m (r: 72 cm) are composed of bricks and mortar (~2 cm in thickness), and filled with rubble stones. The blind arches are also exposed without plastering and paint.

Figure 17. One of two blind arches on east elevation of wall portion A.

3.4.2.2.1.3. Buttresses

Three stone masonry buttresses (~ 1.4 x 2.8 x 3.3 m) are supporting the wall portion A between its arches at its east elevation (Appendix C2). The buttresses have triangular facades at the north and south and positioned back to back with the stone masonry wall. The buttresses are composed of rubble stones (~ 20 x 50 cm) and mortar (~2 cm in thickness) and exposed without plastering and paint (Figure 18).

Figure 18. Three buttresses on east elevation.

3.4.2.2.1.4. Wooden Horizontal Lintels

The wooden lintels (Ø: 8 cm) which are used to support the arches are seen in the remaining arches of the wall portion B (h1:16.80 m, h2:17.15 m). The lintels are in east-west direction (Appendix C2).

3.4.2.2.1.5. Iron Reinforcement

Six iron bars (Ø: 2 cm, L: 5.10 cm) are used on the remaining arches of the wall portion A to support the demolished parts of the wall in north-south direction (Appendix C2). There are on the arch remains which are at the southern end of the wall portion (Figure 19).

Figure 19. Three of six iron bars used to support remaining arches.

3.4.2.2.2. Architectural Elements

The architectural elements are the ducts of the wall with two different materials; stone duct and concrete covered stone duct.

3.4.2.2.2.1. Stone Duct

The stone masonry duct with U profile is (L1: 17.51 m / w: 184 cm / 60 – 90 cm in depth) above the wall portion A in north west direction. The stone duct is composed of rubble stones, corner stones and mortar, and exposed without plastering and paint (Appendix C2 and Figure 20).

The stone duct (L: 25.80 m / w: 168 cm / 68.80 cm in depth), which is above the wall portion B in north west direction, is composed of rubble stones and mortar and exposed without plastering and paint (Appendix C2).

The remain of stone duct (L: 15.11 m) above wall portion A is between incomplete concrete covered stone duct and concrete covered stone duct. The remain is composed of rubble stones and mortar and exposed without plastering and paint (Appendix C2, Figure 21).

Figure 20. Stone duct above wall portion A.

Figure 21. The remain of stone duct above wall portion A.

The remain of stone duct (L:1.00 m / w: 175 cm / 60 cm in depth) is above wall portion C is composed of rubble stones and mortar and exposed without plastering and paint (Appendix C2, Figure 16).

3.4.2.2.2.2. Concrete Covered Stone Duct

Concrete covered stone duct is composed of two parts (L: 18.90 m / w:172 cm / 60 – 90 cm in depth and L: 13.20 m / w:179 cm / 60 – 90 cm in depth) with U profile is above wall portion A in north west direction. The duct is constructed by stone and covered with concrete from the inside of U profile (Appendix C2 and Figure 22).

Figure 22. Concrete covered stone duct above wall portion A.

Incomplete concrete covered stone duct (L: 9.05 m) piece is at the south of the concrete covered stone duct above the wall portion A (Appendix C2 and Figure 23).

Figure 23. Incomplete concrete covered stone duct above wall portion A.

3.4.2.3. Structural Failures, Material Deteriorations and Alterations

In different parts of the wall some structural failures, material deteriorations and alterations threat the integrity and authenticity of the wall (Appendix D1).

3.4.2.3.1. Failures

Three structural failures are observed at the aqueduct wall; demolishment, out of plumbness and fractures.

3.4.2.3.1.1. Demolishment

The parts between wall portion A – B and wall portion B – C, 88 m from northern end with 40 m length and 154 m from northern end with 9 m length, were demolished. These demolishment jeopardize the stability of the wall and have caused loss of structural integrity (Appendix D2, Figure 16 and 24).

Figure 24. The demolished part between wall portions A and B.

3.4.2.3.1.2. Out of Plumbness

The wall portion A and wall portion B lean to different directions and these need to be controlled. Wall portion A leans to east direction (2°) and wall portion B leans to west direction (1°) (Appendix D2, D6 and D7).

3.4.2.3.1.3. Fracture

Three different types of fractures are observed during the site survey on the stone masonry wall and on the brick arches (Appendix D2 and Figure 25). Horizontal fractures (F: 2.20 m) are along arch-wall connections in east-west direction, as observed in the cross sections. Vertical fractures (F: ~ 1.20, 2, 2.50 m) are on the walls continuing from top to bottom. Diagonal fractures (F: ~ 0.90 m) are within the arches, as observed in the cross sections.

Figure 25. The fracture on wall portion A.

3.4.2.3.2. Material Deteriorations

The loss of material and discoloration are the material problems of the wall.

3.4.2.3.2.1. Loss of Materials

Loss of materials is widespread on the surfaces of the brick arches and stone duct (Appendix D2).

3.4.2.3.2.2. Discoloration

Discoloration is seen on iron bars because of corrosion. Wooden horizontal lintels, bricks and plasters have lost their original colors (Appendix D2). Probable cause may be air pollution.

3.4.2.3.3. Alterations

Alterations are defined under two titles; interventions and the losses of the wall.

3.4.2.3.3.1. Interventions

The main interventions of the wall are the additions and reconstructions.

3.4.2.3.3.1.1. Structural Additions

Some structural additions are applied to the wall portion A of the aqueduct to sustain its structural integrity. One of the structural additions is an arch system of wall portion A with two new arches and stone-brick wall under its southern arch (Appendix D2 and Figure 12). The other structural addition is the construction of stone masonry buttresses to the east facade of wall portion A (Appendix D2, Figure 18). Iron reinforcements are used to support the demolished part of wall portion A (Appendix D2 and Figure 19).

3.4.2.3.3.1.2. Reconstructions

The duct of wall portion A is reconstructed with stone and covered with concrete partially (Appendix D2 and Figure 22). However, some part of this concrete covered stone duct is incomplete (Appendix D2 and Figure 23).

3.4.2.3.3.2. Losses

Some of the wall losses are observed in architectural elements.

3.4.2.3.3.2.1. Architectural Element Loss

A part of the stone duct on wall portion A, 23 m from north corner and 56 m in length, is lost between incomplete concrete covered stone duct and stone duct (Appendix D2, Figure 21).

3.5. Seismic Resistance Assessment of the Aqueduct

Vezirağa Aqueduct is at risk of collapse at a probable future moderate earthquake because İzmir is in first degree earthquake zone. The effects of earthquake on the structure can be investigated by the estimation of structural characteristics. The structural analysis of a structure under earthquake loads can be classified as dynamic analyses and equivalent static analysis. Dynamic analyses can be performed by time-history analysis or modal superposition analysis. Time-history analysis helps to define the design forces and displacements of structure under seismic loads showing the whole history of the response and the maximum effects can be determined from the time-history of the response. On the other hand, modal superposition analysis provides the maximum effects via response spectra to reveal expected dynamic action. Response spectra is generated for a earthquake record or a set of earthquake records to represent the maximum response for single freedom system (Paulay and Priestly, 1992). On the contrary, in practice equivalent static analysis is preferred since its ease in implementation. The seismic load which is dynamic in nature is transferred to a static equivalent lateral load mostly influenced by first natural vibration period of the structure. Although there are limitations of use of this method, due to the assumptions made in the transformation of the dynamic load to equivalent static load, it has been widely accepted to investigate lateral performance of the structures.

In order to investigate the acceptable limits and the out-of-plane seismic resistance of the aqueduct, in this study equivalent static analysis for investigating the stability of masonry piers under their own weight and an eccentric top load (La Mendola and Papia, 1993) and dynamic analysis by using finite element model and time-history analysis method to understand the behavior under the earthquake activity have been used.

3.5.1. Equivalent Static Analysis

The earthquake may create a risky loading when the ground motion is out-of-plane to a high structure or wall. Overturning on the wall may occur with the effect of inertia force which may generated by probable earthquakes. Because of the overturning by inertia forces, the risk of collapse or damage can increase especially during an earthquake. Out-of-plane seismic analysis are applied to obtain seismic resistance of a historical structure and to use the results for the structural intervention decisions.

The loading condition can be assumed by loading increaing lateral loads to the wall under their own weight. The analytical procedures are performed to obtain the value of critical loading for the limits of the masonry wall. These analytical procedures help to get deflection curve.

Vezirağa Aqueduct is located on Yeşildere Street in three wall portions which are 81.30 m, 26.30 m and 1 m in length in north-south direction. The demolished parts pose collapse risk for wall portions under lateral loads.

The out-of-plane seismic analysis are performed by equivalent static lateral load analysis to identify the curvature at the top and the maximum inertia forces under the own weight of the aqueduct and the eccentric top load. Hence, the most slender parts of wall portion A and B which are the highest piers are selected to analyze (Figure 26, 27, 28 and 29). The piers are assumed as they are fixed to the ground, free at the top, and strong enough to any compressive forces with no-tension material. Under these circumstances, their own weight and increasing lateral eccentric loads are applied on the structure to determine the resistance of the aqueduct against the out-of-plane forces. The numerical model of La Mendola and Papia (1993) is used for the determination of the resistance.

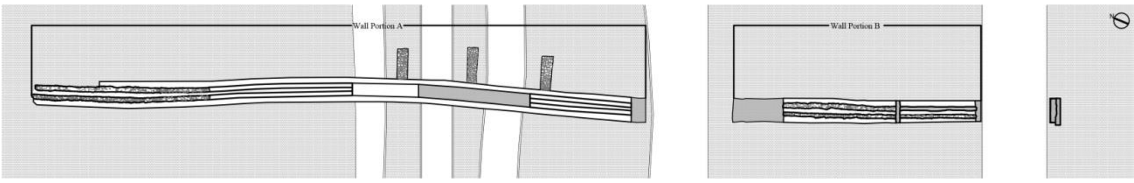


Figure 26. Key plan showing wall portion A and B.

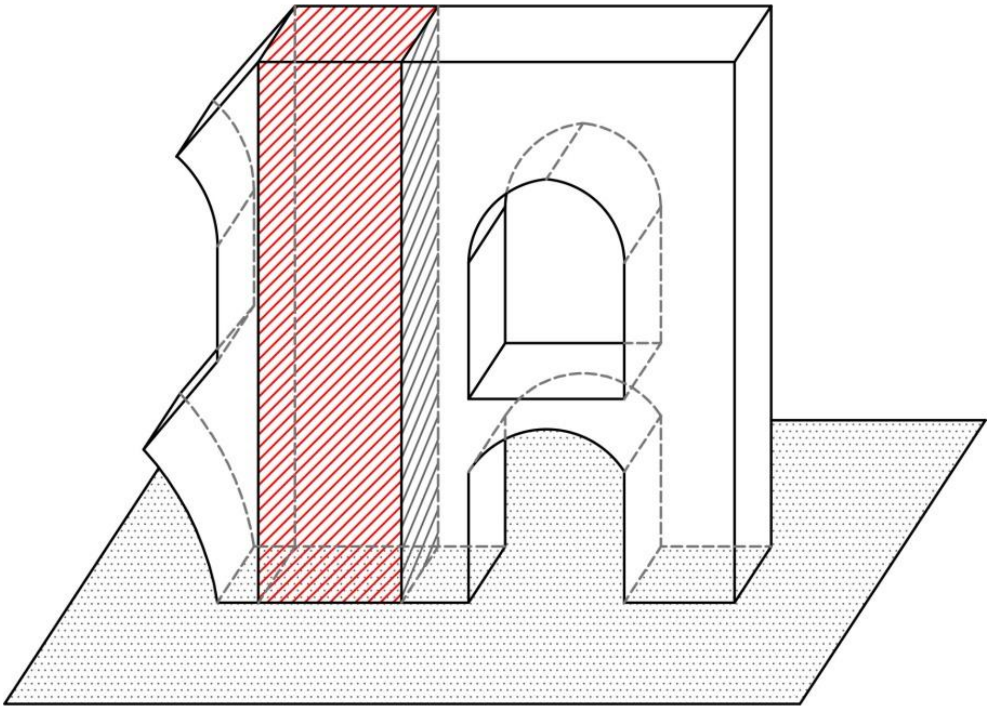


Figure 27. Determination of the pier of wall portion A to use during the out-of-plane seismic analysis.

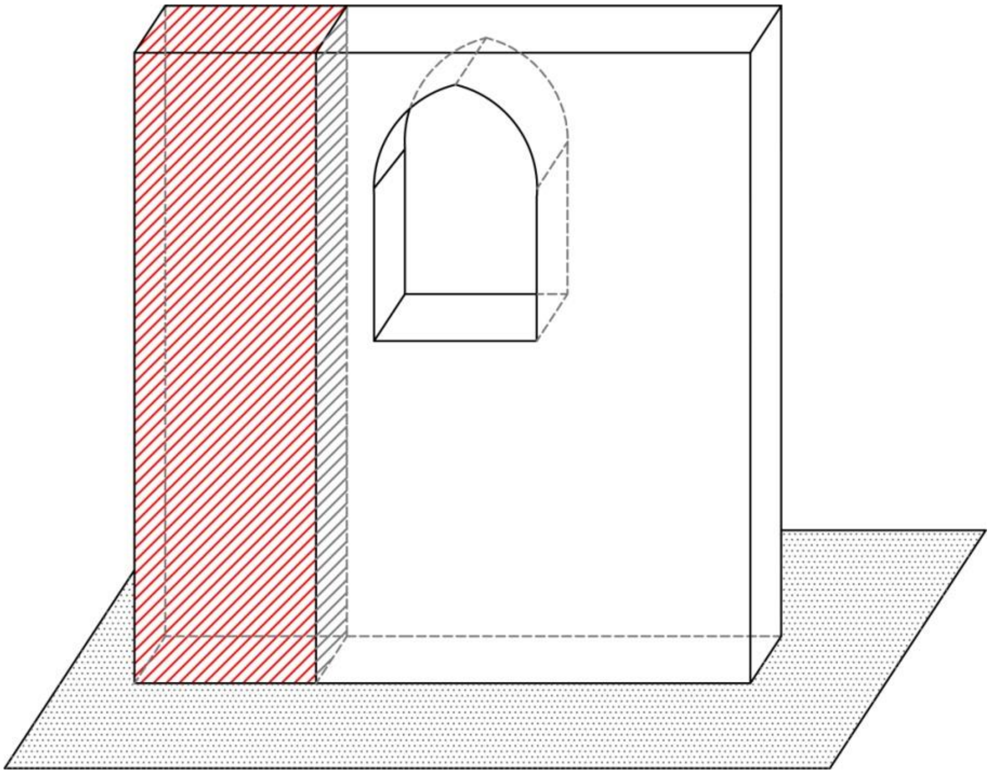


Figure 28. Determination of the pier of wall portion B to use during the out-of-plane seismic analysis.

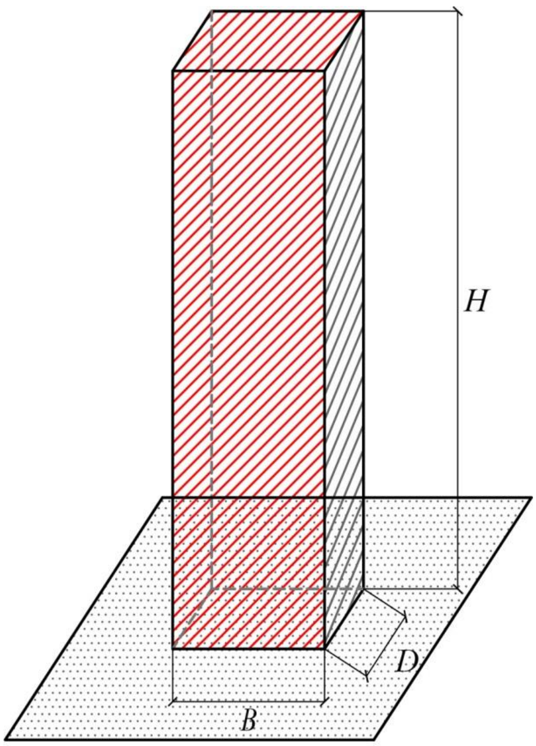


Figure 29. The highest and the most slender pier.

3.5.1.1. Analysis Model

The pier has shown in Figure 58 with H in height, B in width and D in depth. The pier is divided into n elements vertically with the same height in $H_e = H/n$. The elements are numbered from 1 to n from the top to the bottom and the cross-sections are numbered from 0 to n by having $n+1$ cross-sections. The pier has the weight of $W = BDH\gamma$ and the elements has the weight of $W_e = W/n$. The horizontal inertia force applying on one piece is stated with f_j, where j defines the number of element. f_j is linked with W_e and c_j which is the seismic coefficient to identify the intensity of earthquake loading (Figure 30).

$$f_j = c_j \frac{W}{n} = c\left[\left(n - j + {}^{1}\!/_{2}\right)/\left(n - {}^{1}\!/_{2}\right)\right]\frac{W}{n} \tag{1}$$

W_e and f_j is applied to each element and f_j creates a triangular lateral loading forthe whole structure to learn the collapse limit of the structure (Figure 30).

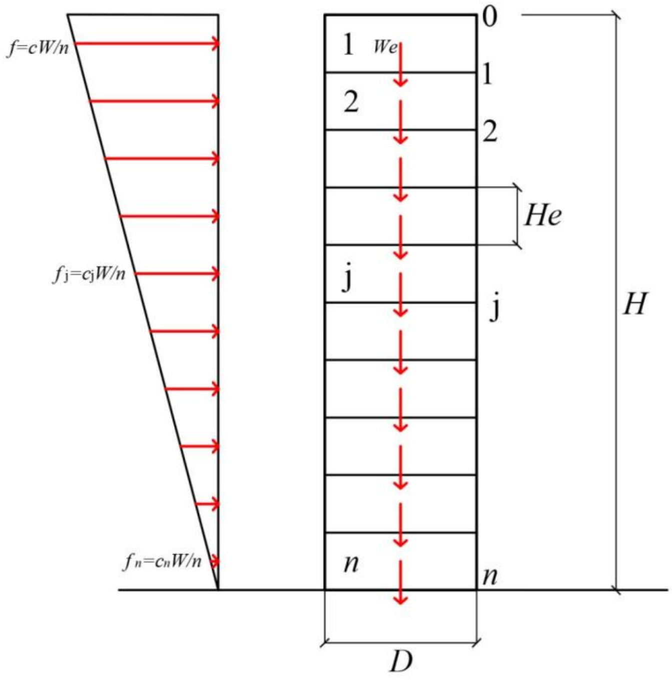


Figure 30. The lateral loading condition of the pier.

The number of pieces n is identified by the calculation of discretization parameter (dimensionless height of the pieces) $\xi = H/nD = H_e/D$. The discretization parameter should be between 0.20 and 0.25 to have the appropriate results from the numerical model.

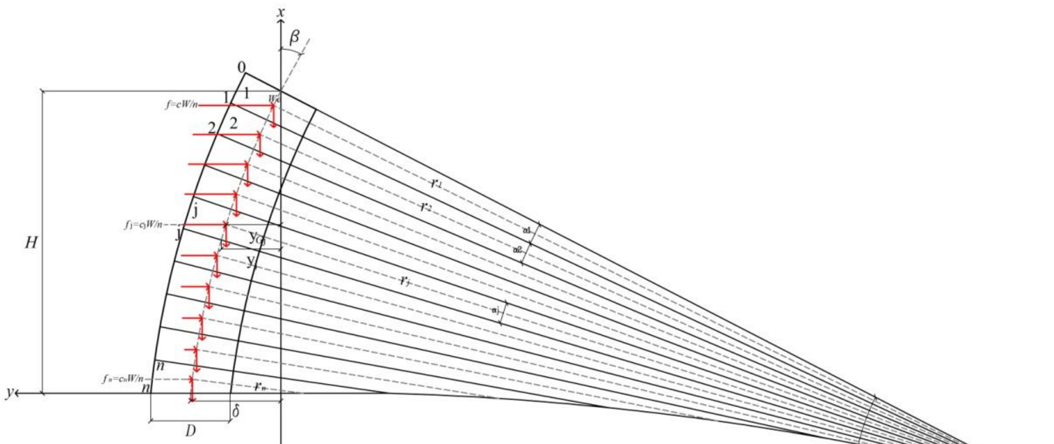


Figure 31. The deformed shape of the pier under its own weight and the lateral eccentric loads.

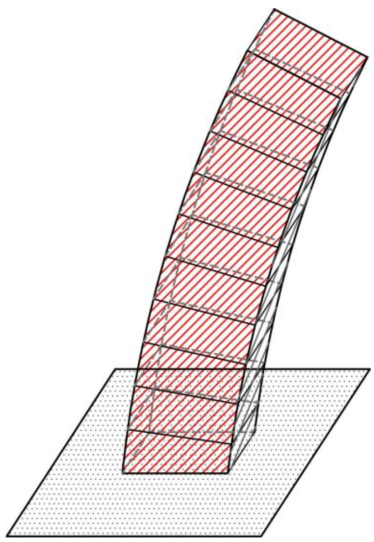


Figure 32. The deformed shape of the pier in three dimension.

The numerical model is used to get the curve of $c - \delta$ where δ (can be defined as y_{Gj}) is the deflection (the horizontal distance of the element from the centre of gravity of the element to the origin in the deformed shape), the curve of $F-\delta$ and maximum seismic coefficient c_{max} (Figure 31).

$$y_j = y_{j-1} + r_j\left[\cos\left(\beta - \sum_{i=1}^{j}\alpha_i\right) - \cos\left(\beta - \sum_{i=1}^{j-1}\alpha_i\right)\right] \tag{2}$$

$(j = 1, 2, 3, \ldots, n)$

$$\alpha_j = \frac{H_e}{r_j} \tag{3}$$

β: The rotation of the top cross-section

r_j: The radius of curvature of the j^{th} element

α_j: The angle in deformed shape

Using the Taylor's series Equation 2 becomes;

$$\frac{y_j}{D} = \frac{y_{j-1}}{D} + \xi\beta + \frac{1}{2}\xi^2\phi_j D - \sum_{i=1}^{j}\xi^2\phi_i D \tag{4}$$

$(j = 1, 2, 3, \ldots, n)$

$$\phi_i = \frac{1}{r_i} \tag{5}$$

ϕ_i: The curvature of i^{th} element

Because $y_0 = 0$ as seen in Figure 31, by calculating curvature of each element the deformed shape of the pier can be drawn.

$$\phi_{j+1}D = \frac{N_j}{BDE}\lambda_j \tag{6}$$

N_j: The resultant compressive force acting on the j^{th} cross section

$$N_j = j\frac{W}{n} \tag{7}$$

E: Elastic modulus of the material

$$\lambda_j = 12\left(\frac{e_j}{D}\right) \quad for \quad 0 \leq \frac{e_j}{D} \leq \frac{1}{6} \tag{8a}$$

$$\lambda_j = \frac{2}{9\left(\frac{1}{2} - \frac{e_j}{D}\right)^2} \quad for \quad \frac{1}{6} \leq \frac{e_j}{D} \leq \frac{1}{2} \tag{8b}$$

$(j = 0, 1, 2, 3, \ldots., n - 1)$

e_j: Eccentricity of the j^{th} element

$$M_j = \frac{W}{n}\sum_{i=1}^{j}\left(y_j - y_{Gi}\right) + c\frac{H}{n}\frac{W}{n}\frac{1}{(n-1/2)}\sum_{i=1}^{j}(n-i+1/2)(j-i+1/2) \tag{9}$$

The eccentricity is calculated by the ratio between Equation 7 and 9.

$$\frac{e_j}{D} = \frac{y_j}{D} - \frac{1}{j}\sum_{i=1}^{j}\frac{y_{Gi}}{D} + c\xi\frac{1}{j(n-1/2)}\sum_{i=1}^{j}(n-i+1/2)(j-i+1/2) \tag{10}$$

$(j = 0, 1, 2, 3, \ldots., n)$

For $j = 0$ at the top cross-section;

$e_0/D = y_0/D = 0$.

When the Equation 6 and 7 are calculated together the curvature of $(j + 1)^{\text{th}}$ can be written as;

$$\phi_{j+1}D = \frac{\gamma D}{E}\xi j \lambda_j \tag{11}$$

$(j = 0, 1, 2, 3, \ldots., n - 1)$

The distance of the centre of gravity of j^{th} element from the origin, y_{Gj}, is yielded by the following expression which depends on the same procedure with y_j.

$$\frac{y_{Gj}}{D} = \frac{y_{j-1}}{D} + \frac{1}{2}\xi\beta + \frac{3}{8}\xi^2\phi_j D - \frac{1}{2}\sum_{i=1}^{j}\xi^2\phi_i D \tag{12}$$

When the Equation 10, 8a or 8b, 11, 4 and 12 are used in order, the curve of $c-\delta$ and c_{max} can be determined. In order to use the equations, a small value c and a trial value of β are defined and the procedure is applied for the pier.

By approving that the pier is fixed end at the base and there is no rotation at the base;

$$\beta = \sum_{i=1}^{n} \alpha_i = \sum_{i=1}^{n} \xi \phi_i D \tag{13a}$$

$$if \quad \beta - \sum_{i=1}^{n} \xi \phi_i D > 0 \qquad \beta \uparrow \tag{13b}$$

$$if \quad \beta - \sum_{i=1}^{n} \xi \phi_i D < 0 \qquad \beta \downarrow \tag{13c}$$

As seen in Equation 13a, 13b, and 13c β should change according to the difference between β and $\sum_{i=1}^{n} \xi \phi_i D$. So as to stop the procedure a small tolerance value should be chosen which is 0.00005 radians for this pier. When the whole procedure is used for each β coming from the change in c, the maximum seismic coefficient, c_{max}, and the maximum out-of-plane force, F, that the pier can resist by its inertia force can be determined.

$$F = \sum_{i=1}^{n} c\left[\left(n - j + {}^{1}\!/_{2}\right)/\left(n - {}^{1}\!/_{2}\right)\right] \frac{W}{n} \tag{14}$$

The analysis model procedure is applied for the highest and the most vulnerable pier of the masonry aqueduct by using the code that written in Matlab (Appendix E1). At the end of this procedure, the curves of $c-\delta$, $F-\delta$, maximum inertia force F_{max}, and maximum seismic coefficient c_{max} are found out. The constant data coming from the literature review and the piers themselves are shown in following table (Table 5, Appendix E2 and E3).

Table 5. The constant data of stone masonry of wall portion A of Veziraǧa Aqueduct.

	Wall portion A	**Wall portion B**
Number of elements - n	19	29
Height of the pier - H	12.60 m	18.70 m
Depth of the pier - D	3.20 m	3.20 m
Width of the pier - B	3.30 m*	3.30 m*
Density of stone masonry - γ	21 kN/m^3**	21 kN/m^3**
Modulus of elasticity - E	871 Mpa**	871 Mpa**
Discretization parameter - ξ	0.2072	0.2015
Acceleration of gravity - g	9.81 m/s^2	9.81 m/s^2

* It is taken as 1, because there is no effect of B during the procedure
**Ercan and Nuhoǧlu, 2014

According to the results of analysis (Matlab codes generated to perform analysis can be found in Appendix E4 and E5) and the curves of $c - \delta$ and $F - \delta$ (Figure 33, 34, 35 and 36), the piers stand like a linear-elastic element at first. When the piers meet with the first crack, they behave like a non-linear element until the maximum value of $c_{max_A} = 0.342396$ and $c_{max_B} = 0.20338$. While seismic coefficient has the maximum value, the deflections are $\delta_{max_A} = 18.47\ cm$ and $\delta_{max_B} = 30.31\ cm$. The piers reach to their maximum lateral resistance.

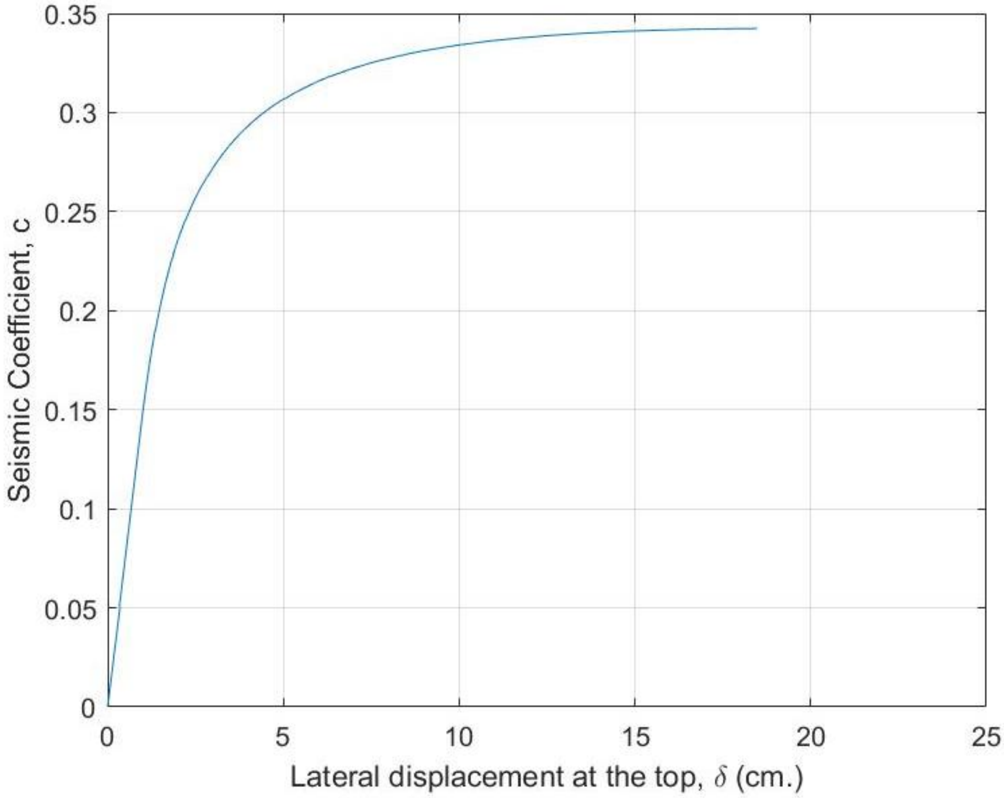


Figure 33. The curve of $\boldsymbol{c} - \boldsymbol{\delta}$ for wall portion A.

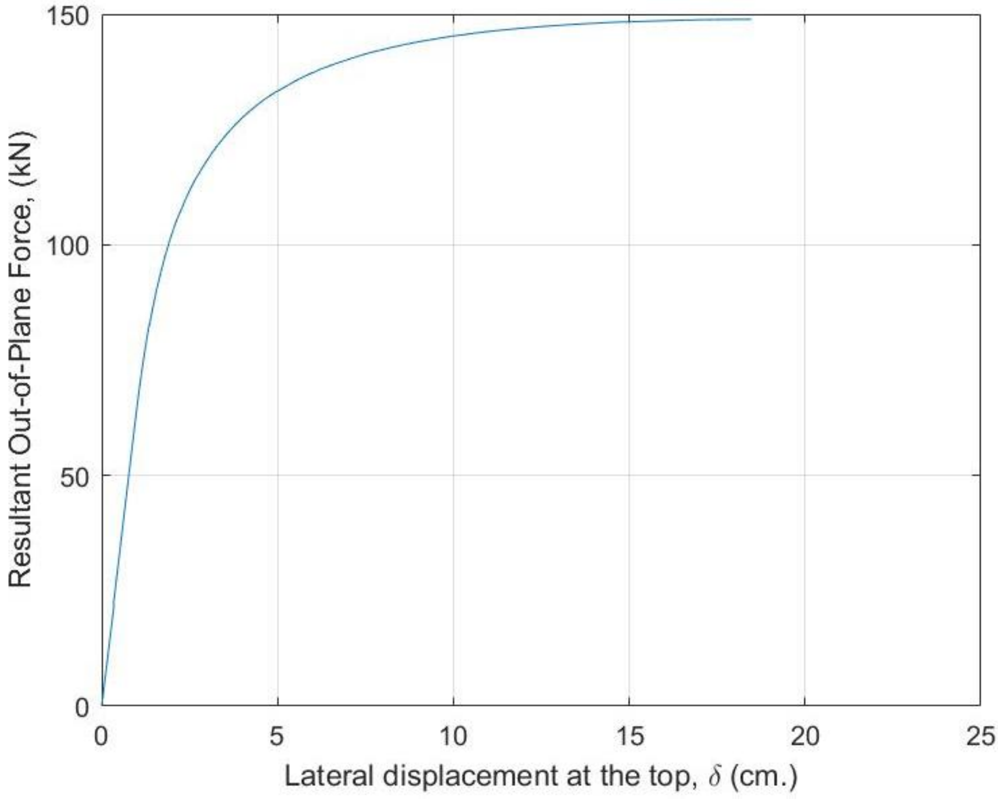


Figure 34. The curve of $\boldsymbol{F} - \boldsymbol{\delta}$ for wall portion A.

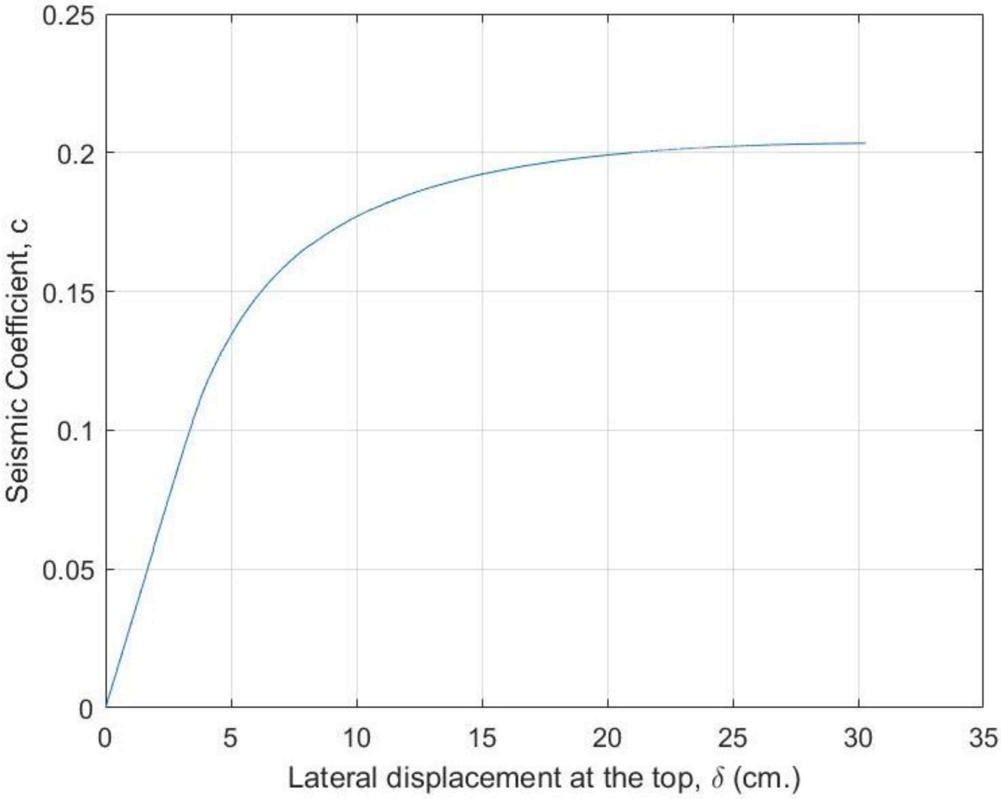


Figure 35. The curve of $\boldsymbol{c}-\boldsymbol{\delta}$ for wall portion B.

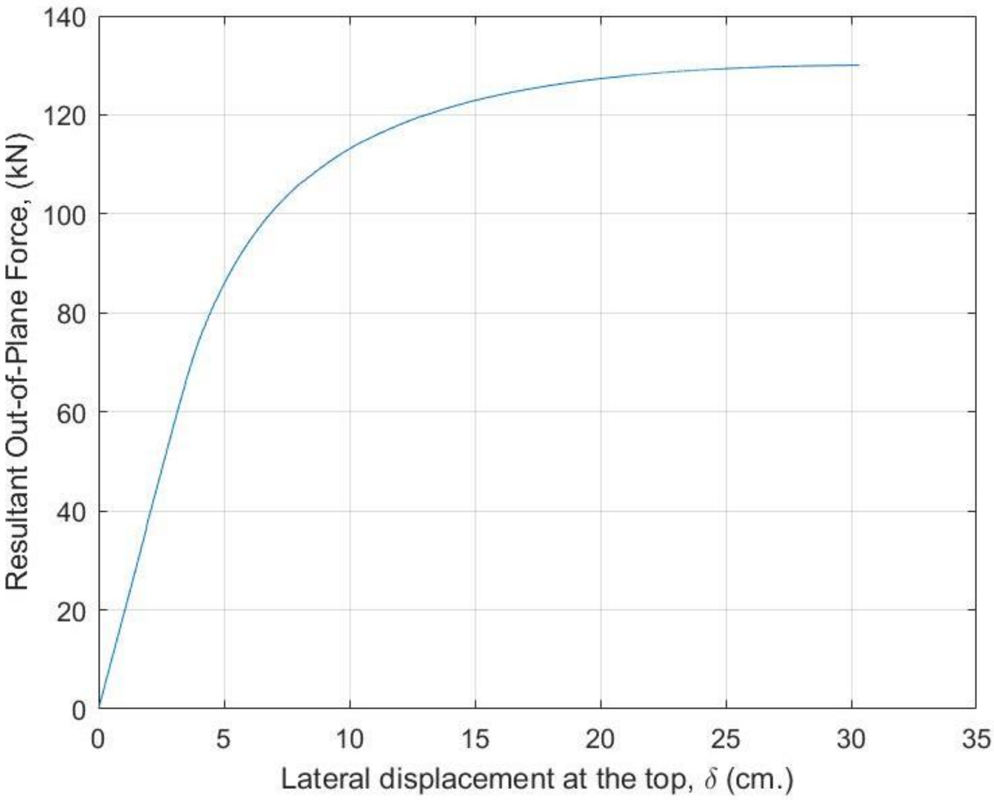


Figure 36. The curve of $\boldsymbol{F}-\boldsymbol{\delta}$ for wall portion B.

By changing Equation 14 as;

$$F_{max} = c_{max} \sum_{i=1}^{n} \left[\left(n - j + {}^{1}/{}_{2}\right) / \left(n - {}^{1}/{}_{2}\right) \right] \frac{W}{n} \tag{14a}$$

$$F_{max} = c_{max} \frac{W}{\left(n / \sum_{i=1}^{n} \left[\left(n - j + {}^{1}/{}_{2}\right) / \left(n - {}^{1}/{}_{2}\right) \right]\right)} \tag{14b}$$

$$F_{max} = c_{max} \frac{W}{1.95} \tag{14c}$$

$$W = Mg \tag{15}$$

The maximum inertia force $F_{max} = F_0$ is obtained by the following equations.

$$F_{max} = F_0 = M_e a_0 \tag{16}$$

M_e: The effective mass of the pier

$$M_e = \frac{3}{4} M \tag{17}$$

a_0: The overturning acceleration

$$a_0 = \frac{F_0}{{}^{3}/{}_{4}\, M} = \frac{c_{max} \frac{W}{1.95}}{{}^{3}/{}_{4}\, M} = \frac{c_{max} \frac{Mg}{1.95}}{{}^{3}/{}_{4}\, M} = \frac{c_{max}\, g}{1.95 * 0.75} \tag{18}$$

g: Acceleration of gravity (Table 8)

The data shown in Table 8 and obtained from Matlab are used in Equation 18. The effective masses of the piers and the overturning accelerations are found out as $M_{e_A} = 64734\ N$, $M_{e_B} = 96073\ N$, $a_{0_A} = 0.23\ g$ and $a_{0_B} = 0.14\ g$

In addition to these results the effective secant stiffness, K_{s-eff}, and the effective natural period of the piers, T_{s-eff}, can be identified to understand the total behavior of the structure under the loads.

$$K_{s-eff} = \frac{F_{\delta_{max/2}}}{\delta_{max}/2} \tag{19}$$

$$T_{s-eff} = \frac{2\pi}{\sqrt{K_{s-eff}/M_e}} \tag{20}$$

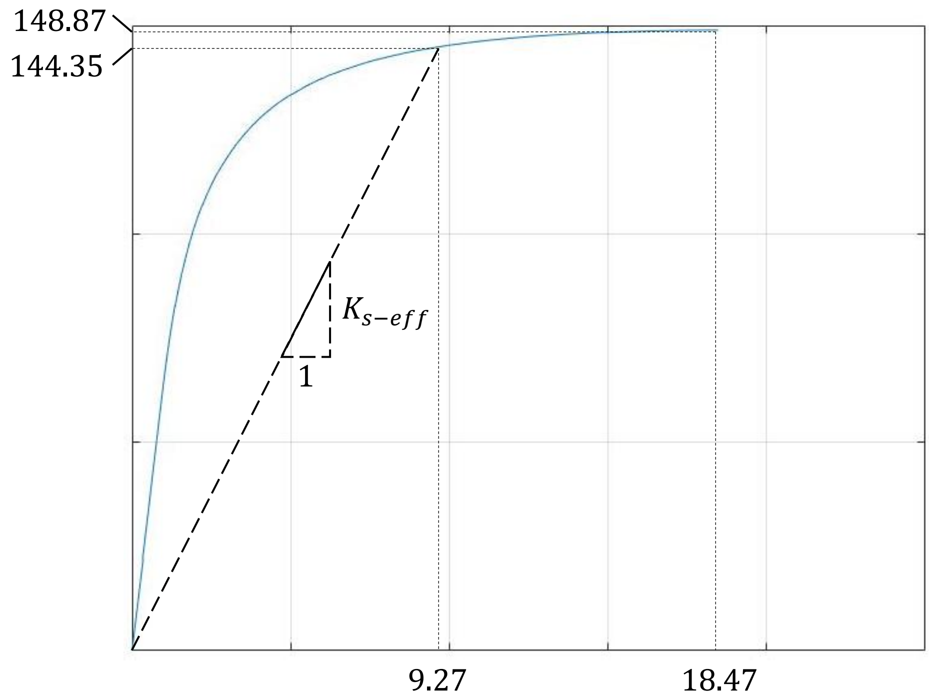


Figure 37. Effective secant stiffness, $\mathbf{K_{s-eff}}$, of substitute structure for wall portion A.

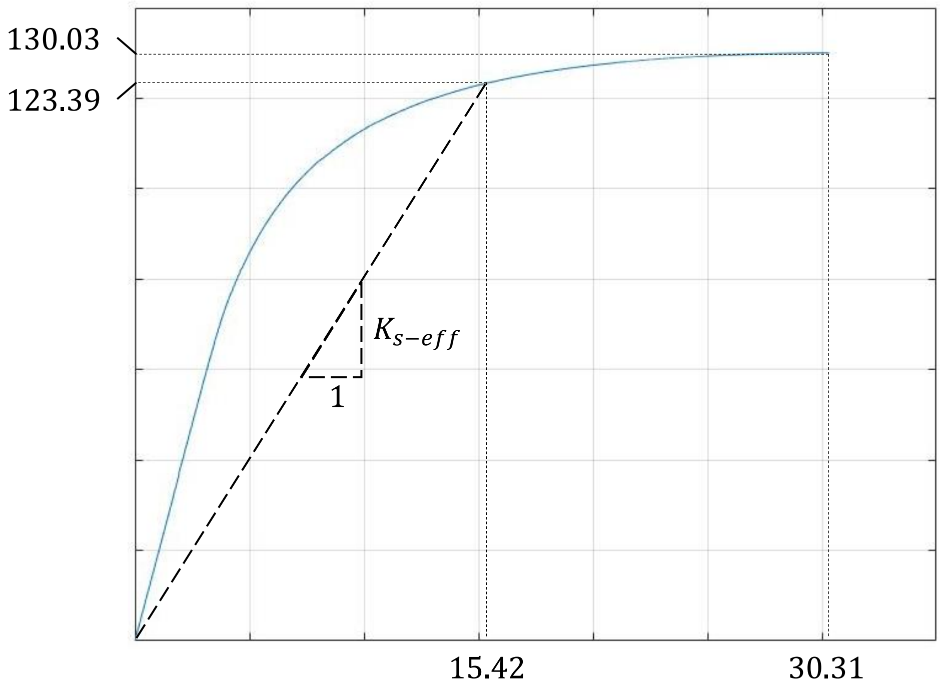


Figure 38. Effective secant stiffness, $\mathbf{K_{s-eff}}$, of substitute structure for wall portion B.

After the calculation of Equation 19 and 20 in order, the effective secant stiffness of the piers are calculated as $K_{s-eff_A} = 1.28$ and $K_{s-eff_B} = 2.17$. The effective natural period of the piers are obtained as $T_{s-eff_A} = 1.28$ s and $T_{s-eff_B} =$ 2.17 s.

The results of the analysis show that the structure can resist the out-of-plane seismic motions in acceptable magnitudes. However, further investigations by taking the seismic characteristics of the site and the damping characteristics of the structure into consideration should be done to reveal the more realistic behavior of the structure under possible loads.

3.5.2. Dynamic Analysis

Finite element method and time-history analysis are used to determine seismic characteristics and simulate the behavior of the aqueduct.

3.5.2.1. Finite Element Modeling

The finite element method is a mathematical modelling approach which allows analyzing the static and dynamic behaviors of the structures under gravitational and lateral loads in 2D or 3D. It is used to define the limits of the structure according to the physical characteristics. It allows investigating the behavior with assumed physical characteristics. In this study the method has been used to obtain dynamic characteristics of the structure to comment on its seismic resistance.

Ercan and Nuhoğlu (2014) had conducted a study on Vezirağa Aqueduct to obtain the material and dynamic characteristics of the structure by experimental and numerical analyses. They made some in situ and laboratory tests for the material characteristics. After the definition of material characteristics by in situ and laboratory tests the modulus of elasticity of stone and brick masonry determined for analytical model. It was determined by the thickness of mortar, height of the unit and the coefficient ρ (taken as 0.5). The material characteristics of the aqueduct are shown in Table 6. Operational modal analysis was also performed to determine the dynamic characteristics of the structure by ambient of wind and traffic excitation. They used

Sap2000 software by using the data in Table 5 to obtain the vibration modes and mode shapes of the aqueduct.

In order to obtain the dynamic characteristics of the structure, two wall portions (A and B) are modeled in SolidWorks to use in Ansys software with finite element method using the material characteristics defined by Ercan and Nuhoğlu (2014) (Table 6). The reasonable results may come from basic models with general geometry of the structure. Therefore, for the modeling of Vezirağa Aqueduct only the general physical characteristics are taken into consideration. Brick and stone parts are modeled with material and physical characteristics. In the aqueduct, the ground levels are defined as fixed supports. Six modes of two wall portions are examined with their frequencies.

Table 6. Material characteristics (Source: Ercan and Nuhoğlu, 2014) to generate finite element model in Ansys.

Material characteristics	**Stone masonry**	**Brick masonry**
Compressive strength (MPa)	10.49	3.62
Tensile strength (MPa)	1.05	0.36
Modulus of elasticity (MPa)	871	201
Shear modulus	326	80.4
Density (kg/m3)	2100	1750
Poisson ratio	0.17	0.17

Wall portion A is modeled with 47355 elements and 176926 nodes. Stone masonry material characteristics are taken from Table 9 which includes the effect of mortar between stones. The finite element model, mode shapes and frequencies of wall portion A are shown below. (Figure 39 and 40, Table 7). The mode shapes are added to Appendix E.

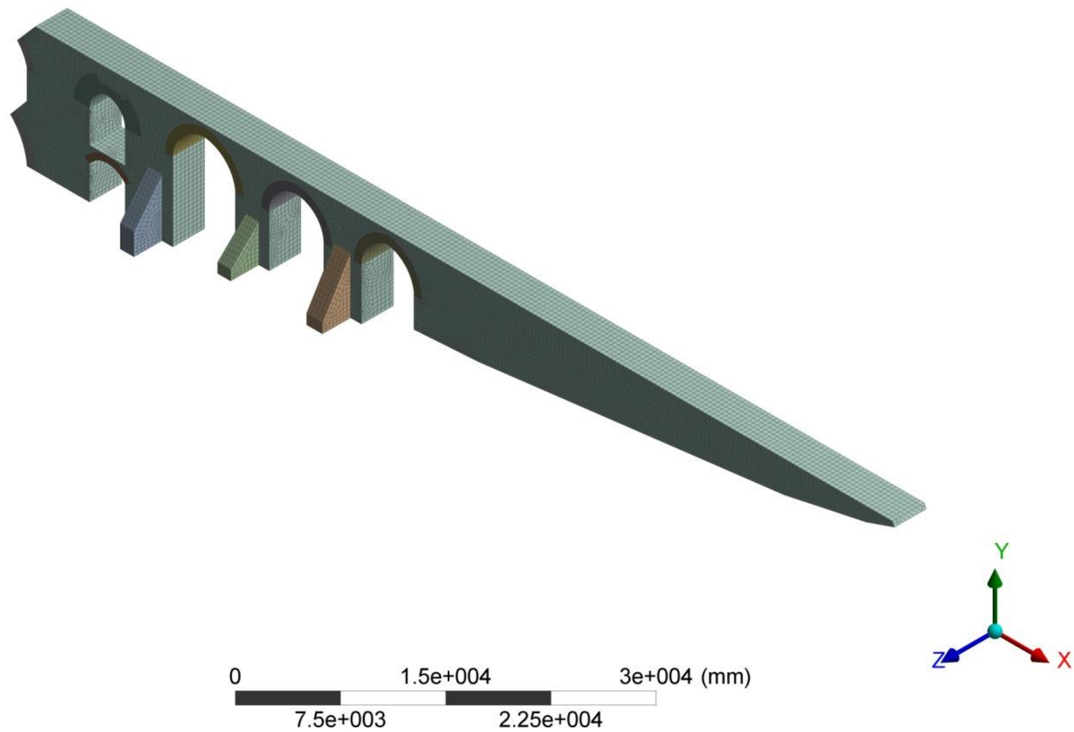


Figure 39. The finite element model of wall portion A.

Table 7. Comparison of frequencies of wall portion A with the analytical and experimental results of Ercan and Nuhoğlu (2014).

Modes	**Frequency (Hz)** (Ansys model)	**Frequency (Hz)*** (Sap2000 model)	**PP Method (Hz)***		**SSI Method (Hz)***	
			Test 1	**Test 2**	**Test 1**	**Test 2**
Mode 1	1.9559	2.877	2.769	2.778	2.758	2.758
Mode 2	3.1015	4.205	4.513	4.542	4.556	4.52
Mode 3	3.9256	5.555	5.413	5.405	5.39	5.375
Mode 4	4.0221	5.83	6.198	6.149	6.08	6.099
Mode 5	5.2391	7.3699	-	7.035	-	7.015
Mode 6	6.5533	-	-	-	-	-

*Parameters of Ercan and Nuhoğlu (2014)

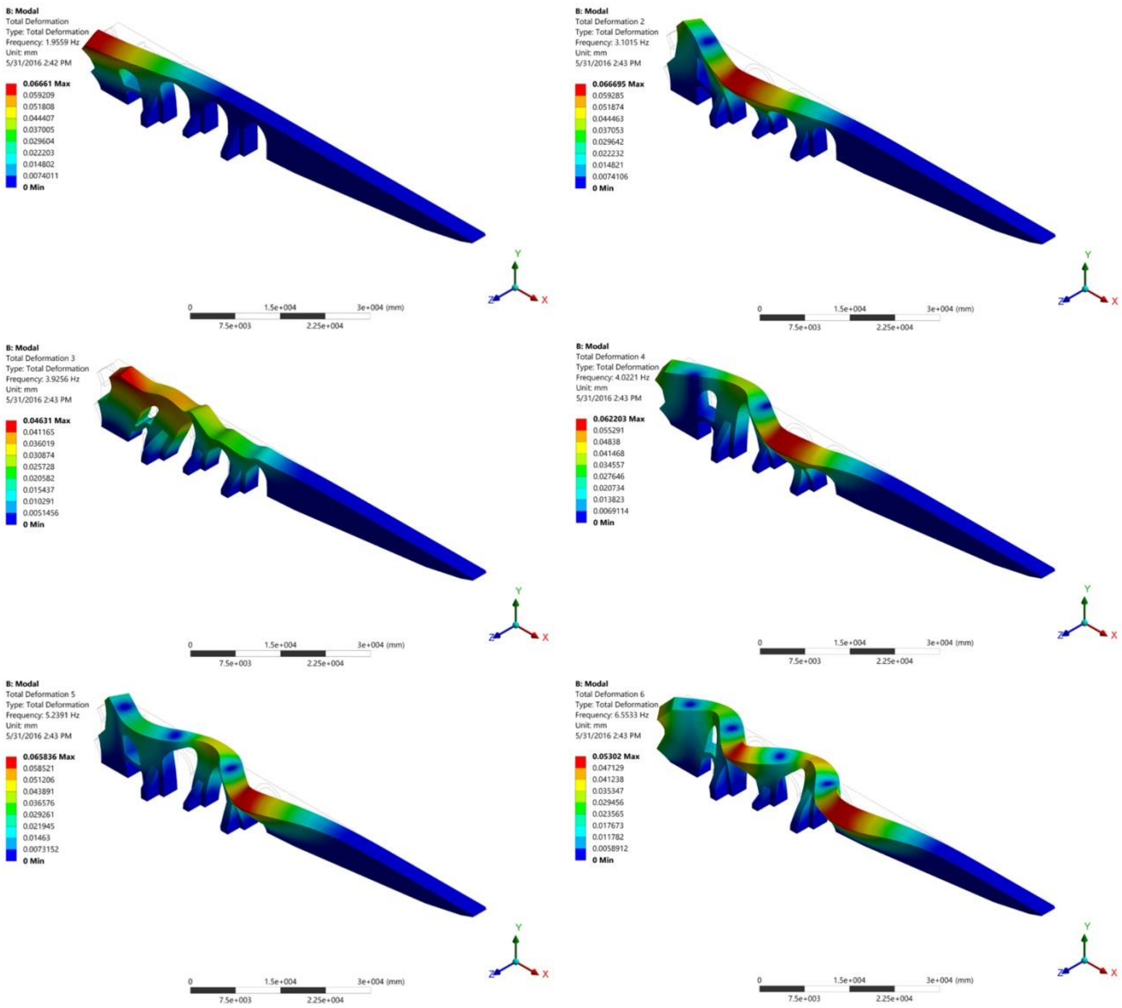


Figure 40. Six mode shapes of wall portion A.

Wall portion B is modeled with 15512 elements and 64926 nodes. Stone masonry material characteristics are taken from Table 5 which includes the effect of mortar between bricks. The finite element model and frequencies of wall portion B are shown below. (Figure 41 and 42, Table 8).

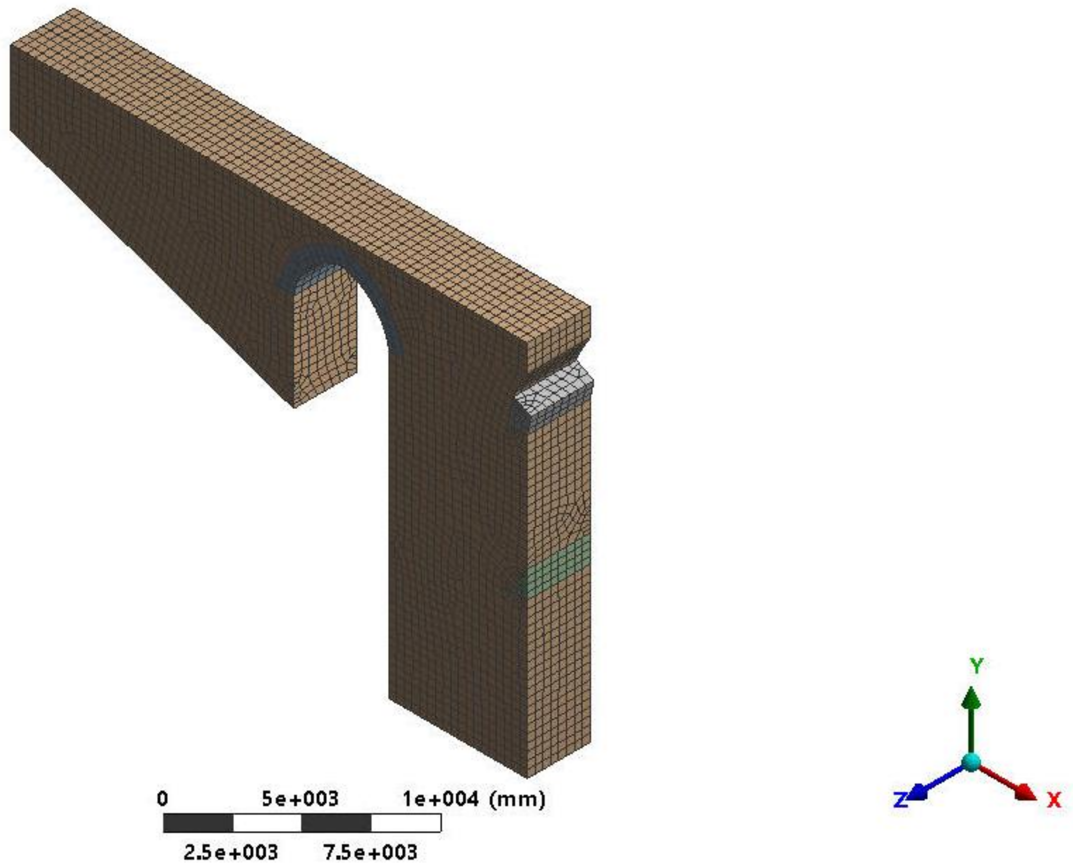


Figure 41. The finite element model of wall portion B.

Table 8. Frequencies of finite element model for wall portion B.

Modes	**Frequency (Hz)** (Ansys model)
Mode 1	1.3993
Mode 2	4.2216
Mode 3	4.5121
Mode 4	4.6251
Mode 5	7.2884
Mode 6	7.705

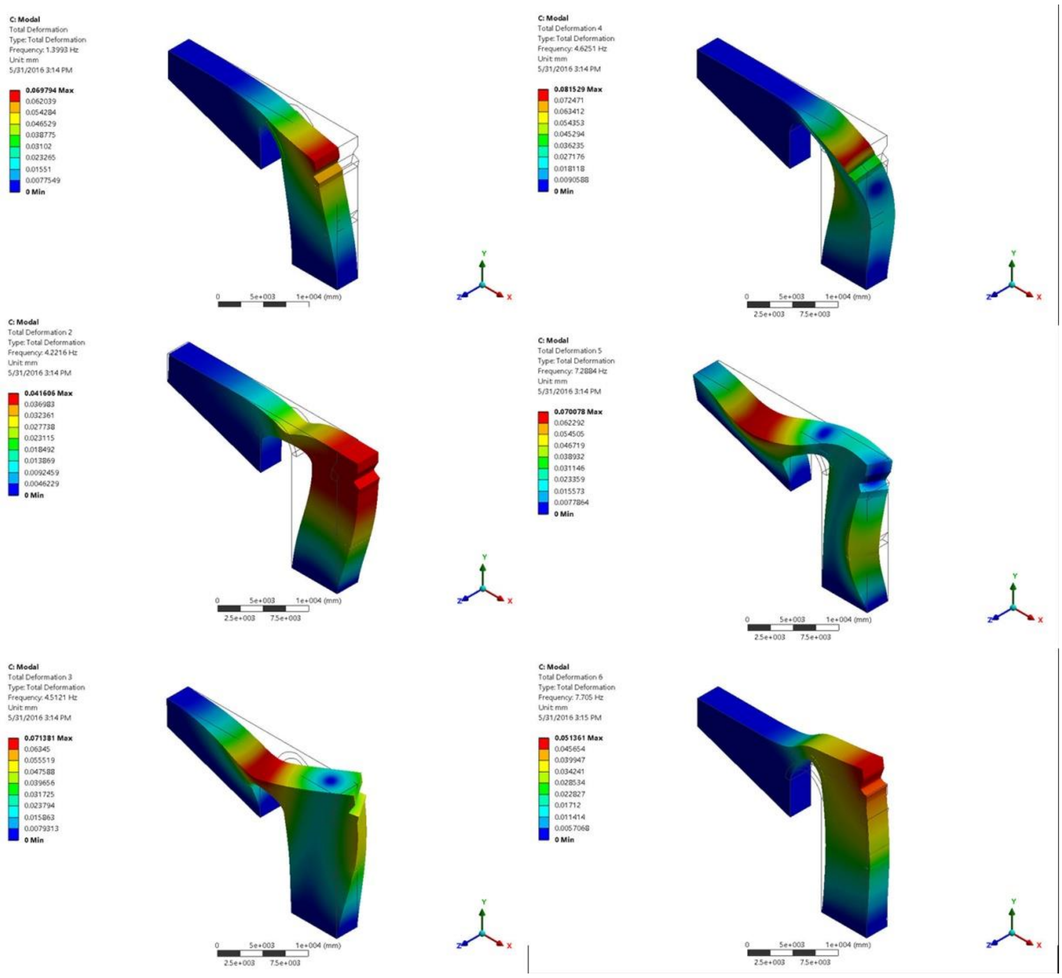


Figure 42. Six mode shapes of wall portion B.

According to the results of equivalent static analysis and dynamic analysis, the structure has slender points that could be at risk of collapse because of the effects of site and the characteristics of the structure. However, in order to say the certain situation the current state of foundation and the detailed analysis on material characteristics should be made and the behavior of the structure should be defined in detail.

3.5.2.2. Time-History Analysis

Time-history analysis can be performed to a structure to determine the behavior, elastic displacements and probable damage locations of the structure for a record of an earthquake excitation.

In this study the record of El Centro earthquake in United States in 18 May 1940 with 7.1 magnitude and a peak ground acceleration (pga) of 0.32 g is applied to the aqueduct (Figure 43). The earthquake lasted thirty two seconds and 80 percent of the buildings had damaged in El Centro.

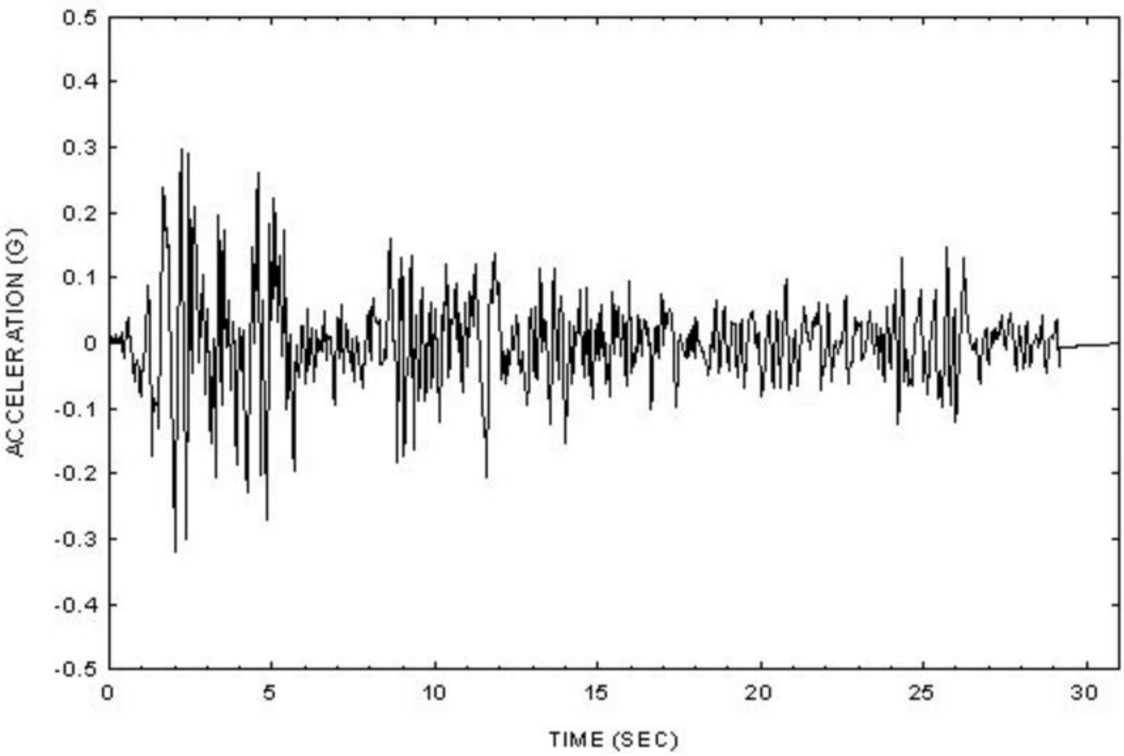


Figure 43. Time-Acceleration data of El Centro Earthquake.
(Source: Vibrationdata, c2015)

The data of El Centro Earthquake is applied to wall portion A for thirty two seconds. The snapshots of the displacements at different times are show in Figures 44 and 45.

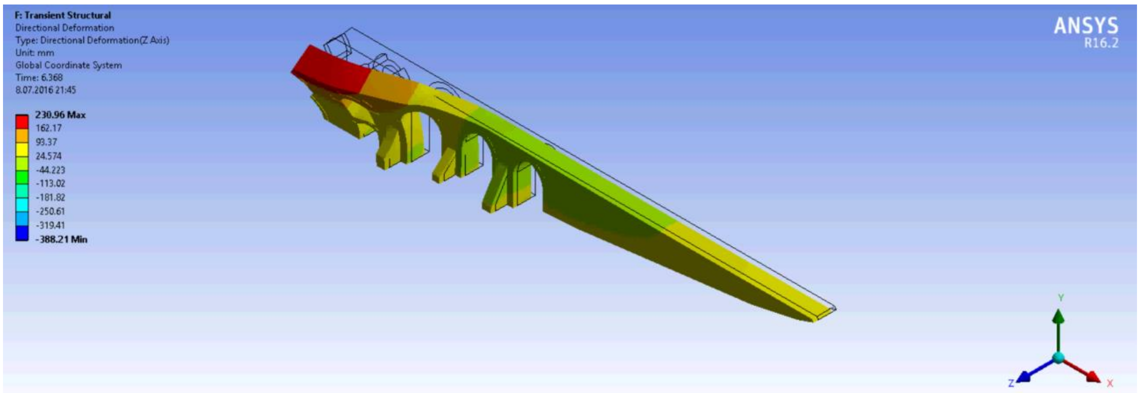


Figure 44. Displacement on plus z direction.

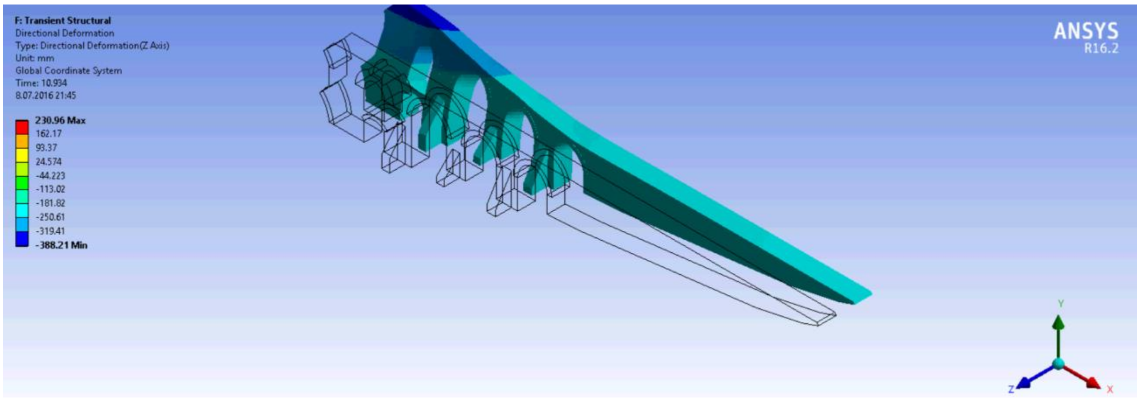


Figure 45. Displacement on minus z direction.

The maximum displacements are around 213.81 mm at the ground at 2.6 s, 388.21 mm at 27.3 s on plus z direction and 230.96 mm at 6.34 s on minus z direction at the top (Figure 46).

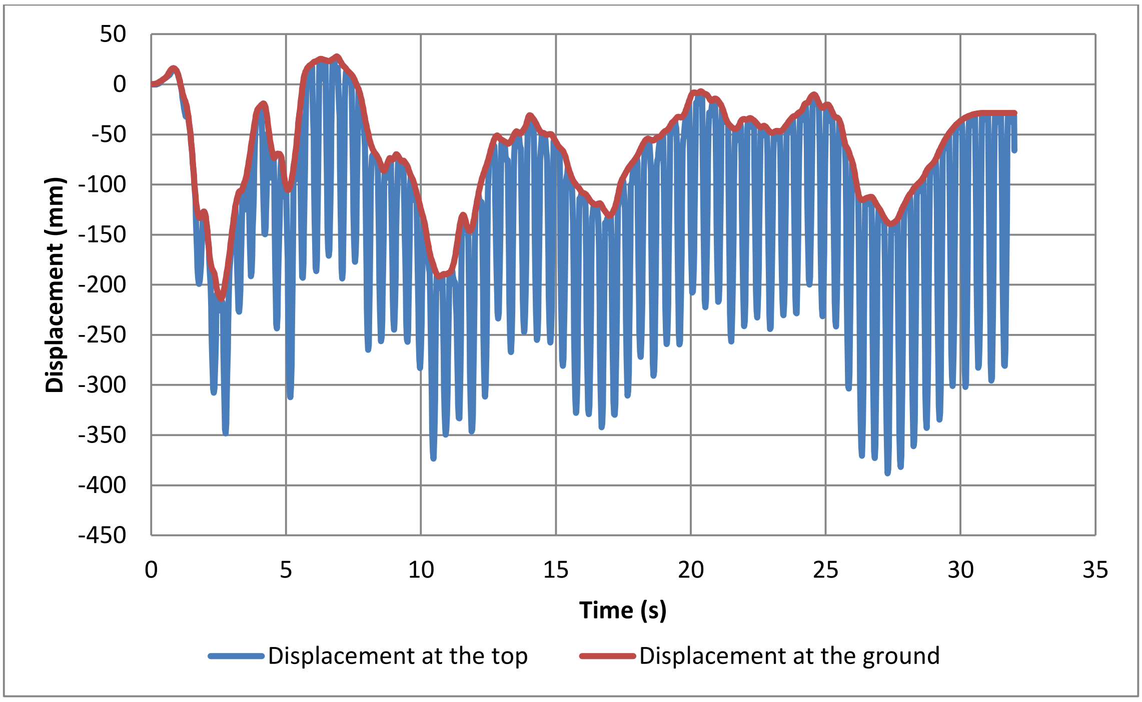


Figure 46. Time-Displacement data at the ground and top for wall portion A.

The relative displacement defines the difference between top and ground displacements at each second. The maximum relative displacement is 268.55 mm at 30.18 s (Figure 47).

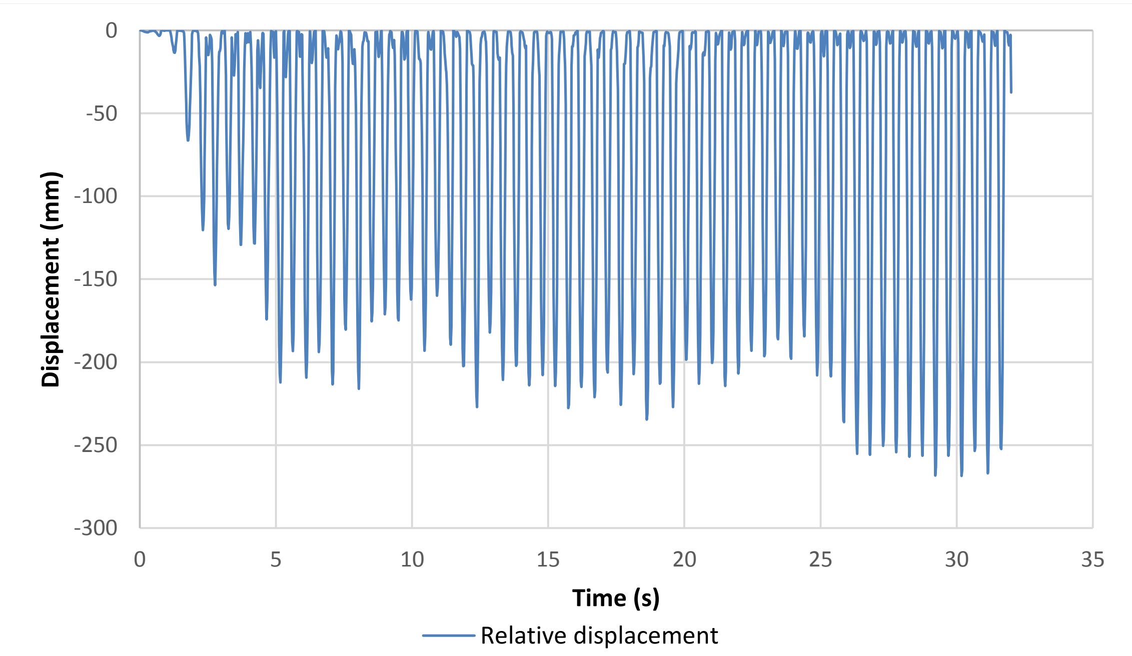


Figure 47. Relative displacement of wall portion A.

CHAPTER 4

HISTORICAL RESEARCH AND COMPARATIVE STUDY

The historical evolution of the city of İzmir with emphasis on the study area, history of ancient water supply systems with an emphasis on those in the study area, and the comparative study with similar examples from Ottoman Period are explained in the below.

4.1. History of the Region

The city was founded in Tepekule/Bayraklı initially. In 4th century BC, the city was re-established in Kadifekale. During the Hellenistic and the Roman periods, the city was located around the port and on the Kadifekale. The two main arteries of the city were running on east-west and south-nourth directions, and monumental buildings such as porticoes, temples, theatre, gymnasium and stadium were the identifying elements of the city from those periods.

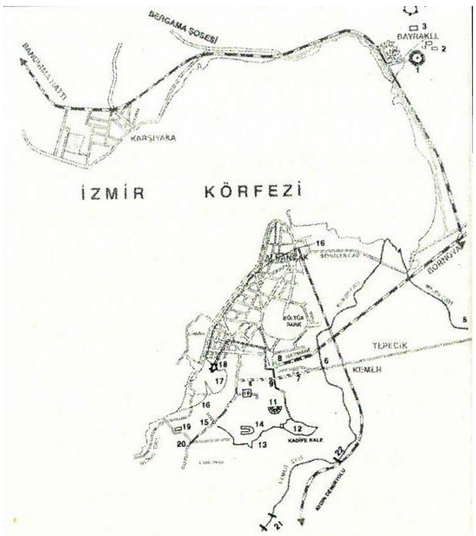


Figure 48. Gulf of İzmir at the first age.
(Source: Yetkin and Yılmaz, 2003a)

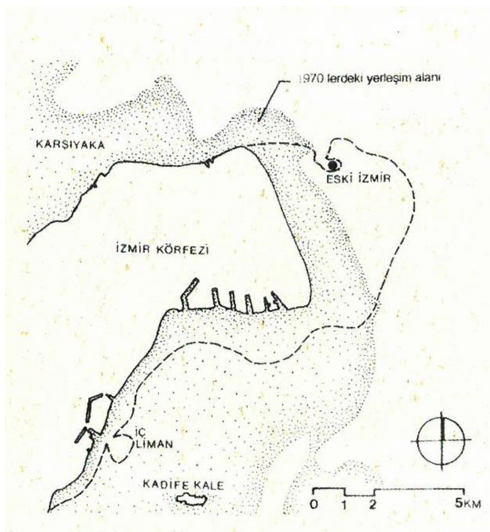


Figure 49. Gulf and city at the first age.
(Source: Yetkin and Yılmaz, 2003a)

The main information about the city and its developments come from the excavations of Kadifekale, Agora and Altınpark. The administrative and commercial center of the city was Agora and the examples of residential units of Roman and Early Byzantine periods were around the Altınpark, out of the city walls. The city walls of Kadifekale dates back to the Hellenistic period. They had been intervened in different periods. There are a cistern and a chapel in Kadifekale from the late Roman Period. (Kayın, 2013, p. 29 – 76).

Figure 50. Kadifekale (Mount Pagos).
(Source: İzmir Metropolitan Municipality, c2015)

After the division of Roman Empire in 395, and the establishment of Byzantine Empire in 476, İzmir was one of the important cities of the era. When Byzantines accepted Christianity as their official religion, İzmir became the religious center of the empire and improved like the capital, Constantinople. Because the temples from the Roman Period were not in line with the beliefs of Byzantines, most of them were demolished. The architectural elements of these monuments were moved to the capital. The reason of protecting the monuments such as aqueduct, Agora and city walls is their utilitarian functions (Yetkin and Yılmaz, 2003a, p. 34 - 39).

Byzantines used these monuments with their original function and they also constructed new buildings. However, during the invasions of Sassanian's and Emevi's in

7th century, the city had lots of demolishment and lost its important monuments. Besides these invasions, "Ikonaklasmus (*Tasvir Kırıcılık Hareketi*)", which means the movement of icon destruction, had lots of negative effects on the city architecture because of the civil war between iconoclasts and the other religious people (Ayönü, 2009, p. 2).

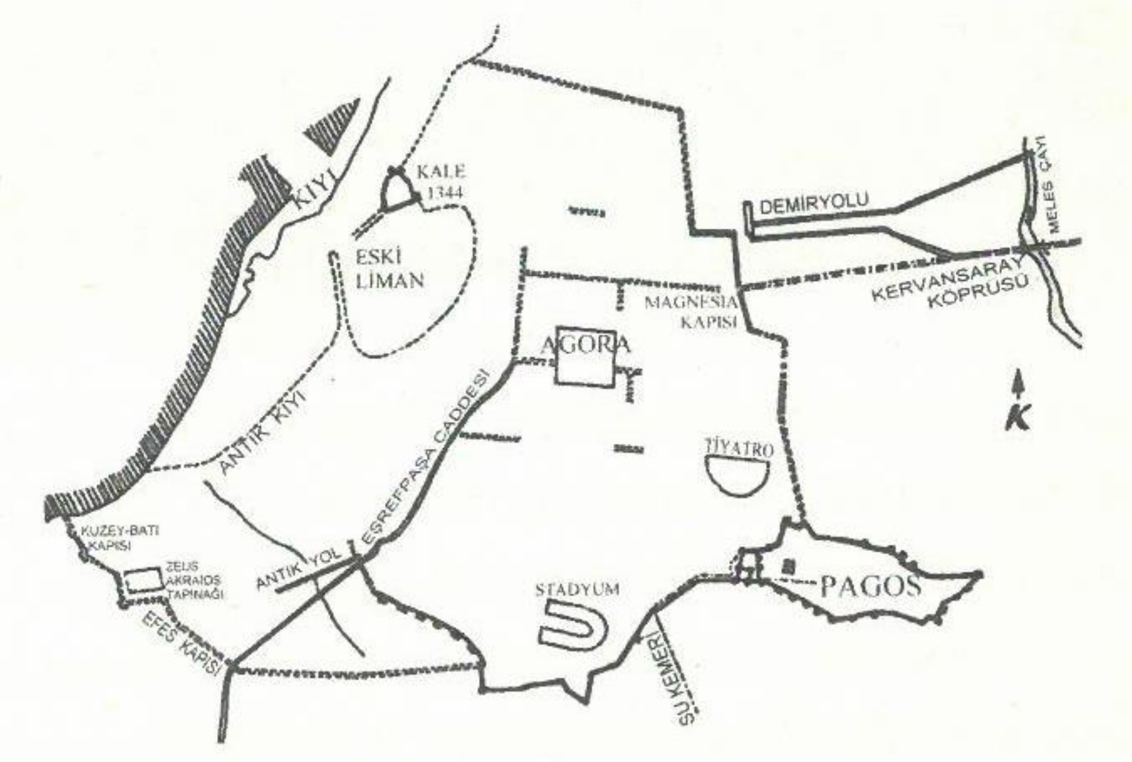


Figure 51. İzmir from the Roman Period.
(Source: Yetkin and Yılmaz, 2003a)

After the victory of Battle of Malazgirt in 1071, contention of Turks and Byzantines on İzmir continued until the city was taken by Çaka Bey in 1081. However, the domination of Çaka Bey in İzmir ended in 1095 with his murder by Kılıç Arslan (Daş, 2013b, 46 – 51).

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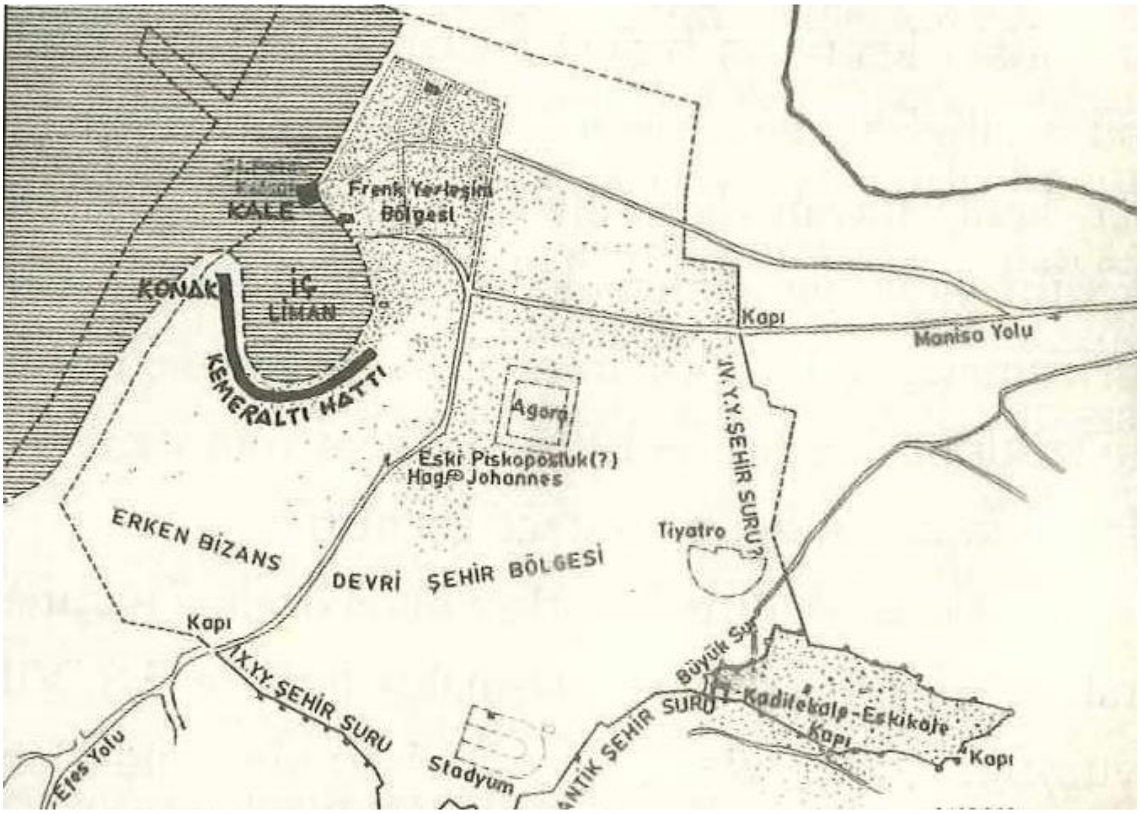


Figure 52. İzmir from the Byzantine Period.
(Source: Yetkin and Yılmaz, 2003a)

In 1096, Byzantines retook the city and controlled it until 1317, when Aydınoğlu Mehmed Bey captured the city. After him, the domination of Turks in İzmir officially started. However, Mehmed Bey could only capture Kadifekale, Liman Kalesi (Port Castle) was under the domination of Latins (Daş, 2013a, 27 – 36). In the 14th century, Latins dominated Liman Kalesi and Turks dominated Kadifekale. The city was divided into two as ‘Aşağı İzmir – Yukarı İzmir’ (Down İzmir – Top İzmir) or ‘Müslüman İzmir – Hristiyan İzmir’ (Muslim İzmir – Christian İzmir). This division was about the architectural characteristics and life conditions on the coast and on the mount. The division created rich cultural and socio – economic characteristic which had an effect on the spatial characteristics of the buildings (Kayın, 2013, p. 29 – 76).

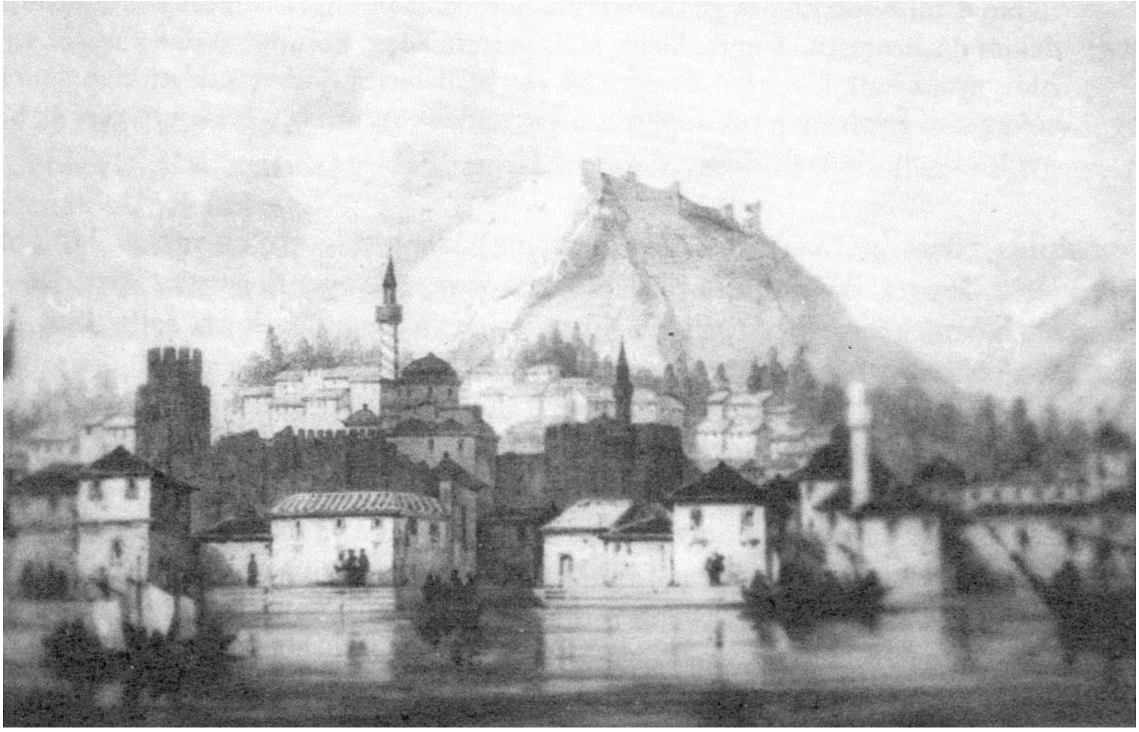


Figure 53. Kadifekale at the back and Liman Kalesi in front.
(Source: Apikam, c2016)

In 14th century, Venetians and Genoveses were quite active in İzmir especially in sea trade. They had their own neighborhood close to the port and built churches, baths and bakeries (Yetkin and Yılmaz, 2003a, p. 34 - 39).

In 1402, Emir Timur came to İzmir and captured Liman Kalesi and demolished the castle. The city was under the control of Turks with this attack (Daş, 2009, 41 – 53).

In 1426, when Ottoman Empire dominated the area, their main settlement was within the city walls of Kadifekale. However, in 1472 with the attack of Venetians to keep their commercial privileges, Mehmet the Conqueror rebuilt Liman Kalesi to protect the city from some other attacks. The agricultural activities were privileging in the city, to fulfil the needs of capital. However, the commercial life of the city began to revitalize between two castles, especially after the conquer of Chios Island and Cyprus. Greeks and Latins came to city and changed the character of the city. During the Ottoman – Persian wars, Aleppo also lost its importance in commercial activities and Armenians started to migrate to İzmir. Besides, Jewishes from villages migrated to the city after this commercial rising. At the end of 16th century, İzmir became the new center of trade in Mediterranean era. Frenches, Dutches, Britishes, Venetians and Genovese’s started to use İzmir port for their commercial activities. Some of them started to move to the city. With this localization, the population increased and this created the need of new settlement areas. Therefore, more residential areas developed starting from the northern skirts of Kadifekale to the port. There were also different ethnic groups as Turks, Greeks, Jewish, Armenians and Levantines in the city. According to their localizations, Turks were living on the northern skirts of Kadifekale. The merchants were living around port in Frenk Neighborhood. Greeks and Jewish people were living in the area between Frenk Neighborhood and Kadifekale. These different groups had lots of influence on the city in the following years especially about the cultural life. (Yetkin and Yılmaz, 2003a, p. 47 - 53).

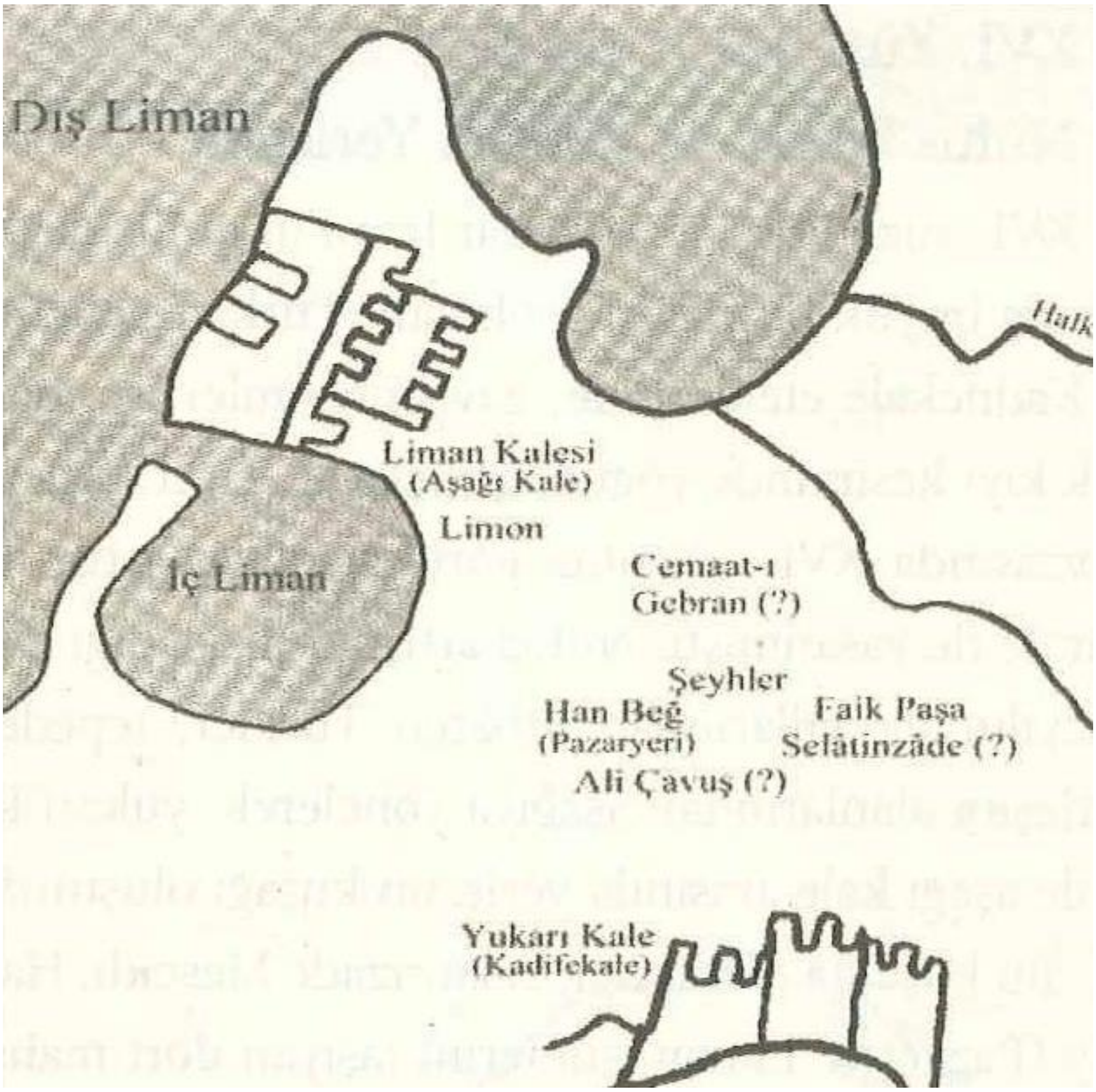


Figure 54: Neighborhoods of İzmir in 16th century.
(Source: Yetkin and Yılmaz, 2003a)

Figure 55. Frenk Street.
(Source: İzmir Metropolitan Municipality, c2015)

In the 17th century, İzmir developed economically and commercially. The reasons of this development are the deep interest of Europa to Levantines to the city for commercial activities, preference of İzmir as trade center by Levantine Company and Ottoman Empire, and movement of English and French Consulate to İzmir from Chios Island. İzmir port served to lots of merchants from Europa and became the main trade port in Mediterranean, while the city center was a passage for the merchants from east (Demirbaş, 2009, p. 55 - 78). Most of the merchants used port and Kervan Bridge (Caravan Bridge) to reach the city from Manisa – Akhisar. Kervan Bridge is located on Gaziler Street at the northeast of the study area today and it is totally renewed (Kayın, 2013, p. 29 – 76).

Figure 56. Kervan Bridge (Caravan Bridge).
(Source: Apikam, c2016)

These developments created a prosperous life and need of new physical opportunities in the city. New shopping areas (bedesten), custom house to control imports and exports, new water lines to fulfill the need of water of the city were built. During this period new khans for commercial activities were built after the construction of two Vezir Khans (*Büyük and Küçük*) by Sadrazam Köprülü Fazıl Ahmet Paşa. This monumental building was an important example for the other khans in the era (Yetkin and Yılmaz, 2003a, p. 47 - 53). The number of khans especially for foreign merchants reached to eighty-two which was twenty-five before 1670. Salt treatment ateliers, coffee shops, ale houses, soup treatment ateliers and rendering plants were built especially around port in Frenk Neighborhood. These new treatment buildings were creating the physical characteristics of the port (Demirbaş, 2009, p. 55 - 78).

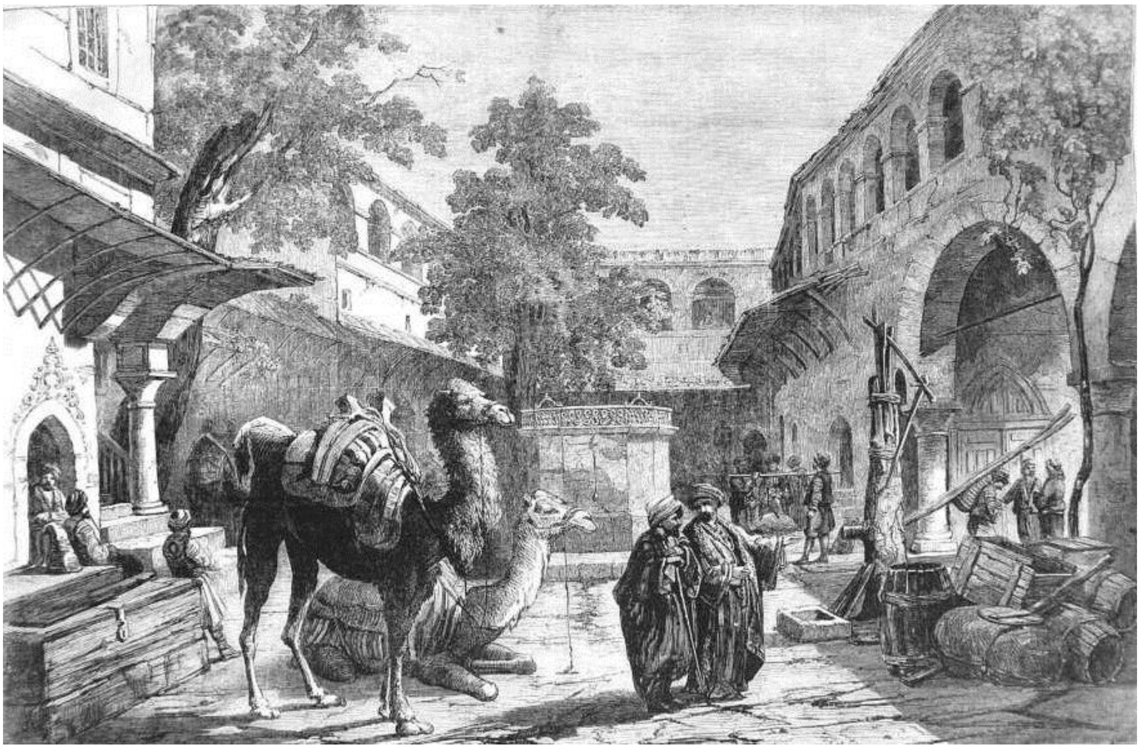


Figure 57. Gravure of a khan in İzmir.
(Source: Yetkin and Yılmaz, 2003a)

The 1688 earthquake and the fire after the earthquake demolished lots of the buildings in the city. However, the city was rebuilt immediately and didn't lose its commercial importance. The commercial activities were carried onto international phase and with this variance the local production got a severe blow. With the control of industrial Europa, the need of raw material especially in İstanbul could not be controlled. In order to support these changes and developments in commercial activities and to fulfill the increasing necessities of the city center, the government made investments such as khans and aqueducts (Yetkin and Yılmaz, 2003a, p. 47 - 53).

18th century is the golden age of İzmir especially for the commercial activities on the port. Until 1740, İzmir was an international port which used as a passage from Asia to Europa. However in the second half of 18th century the need for raw materials and especially cotton in East Europe and America invigorated the commercial activities on the port. Besides İzmir became a world city, instead of being an international city. These developments created the need of new products and places to store them in the city close to the port. The local rulers of the city constructed new khans for both serving commercial activities and using as storages. Mirkelam oğlu Khan, Karaosmanoğlu Khan, Büyük

Demirhan and Küçük Demirhan are the examples of the new khans. İzmir became the most important port city in East Mediterranean era for Europa and for the Ottoman Empire with the new activities and developments (Yetkin and Yılmaz, 2003a, p. 53 - 54).

During the second half of 19th century, the fire department of the city was set up and a fire observation tower was built on one of the bastions of Kadifekale. In 1866, during the period of Sultan Abdulaziz, the İzmir – Aydın railway was built parallel to Yeşildere in Melez valley. Melez valley and Yeşildere were the main reference points of the area and the aqueduct on Yeşildere was focal point of the area (Kayın, 2013, p. 29 – 76).

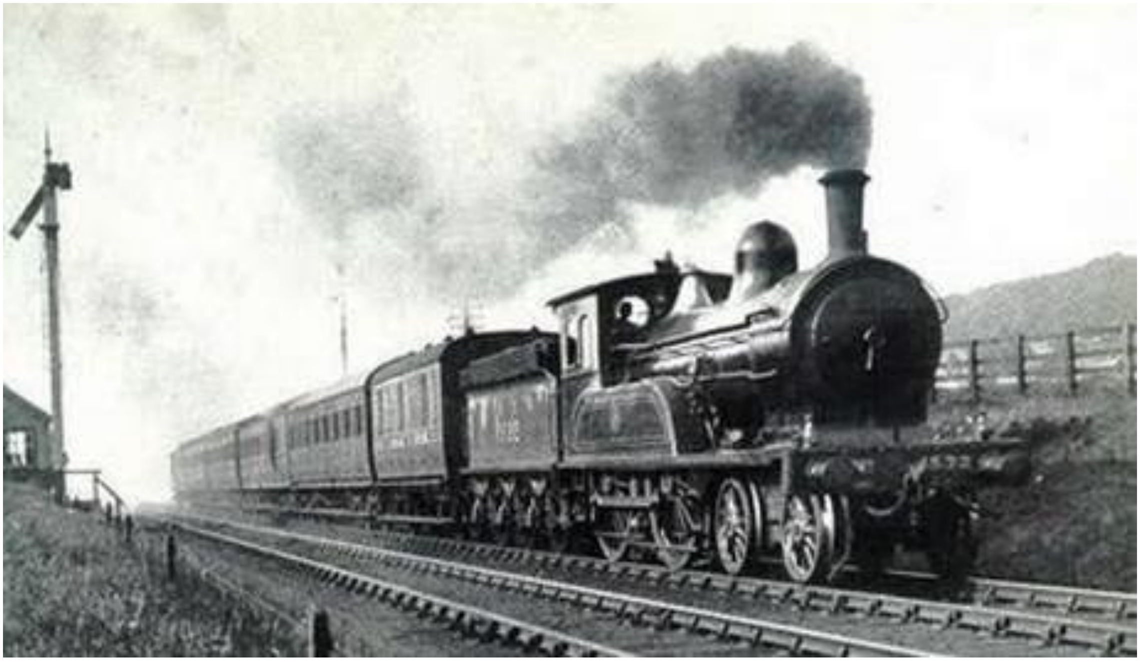


Figure 58. İzmir-Aydın Railway.
(Source: Apikam, c2016)

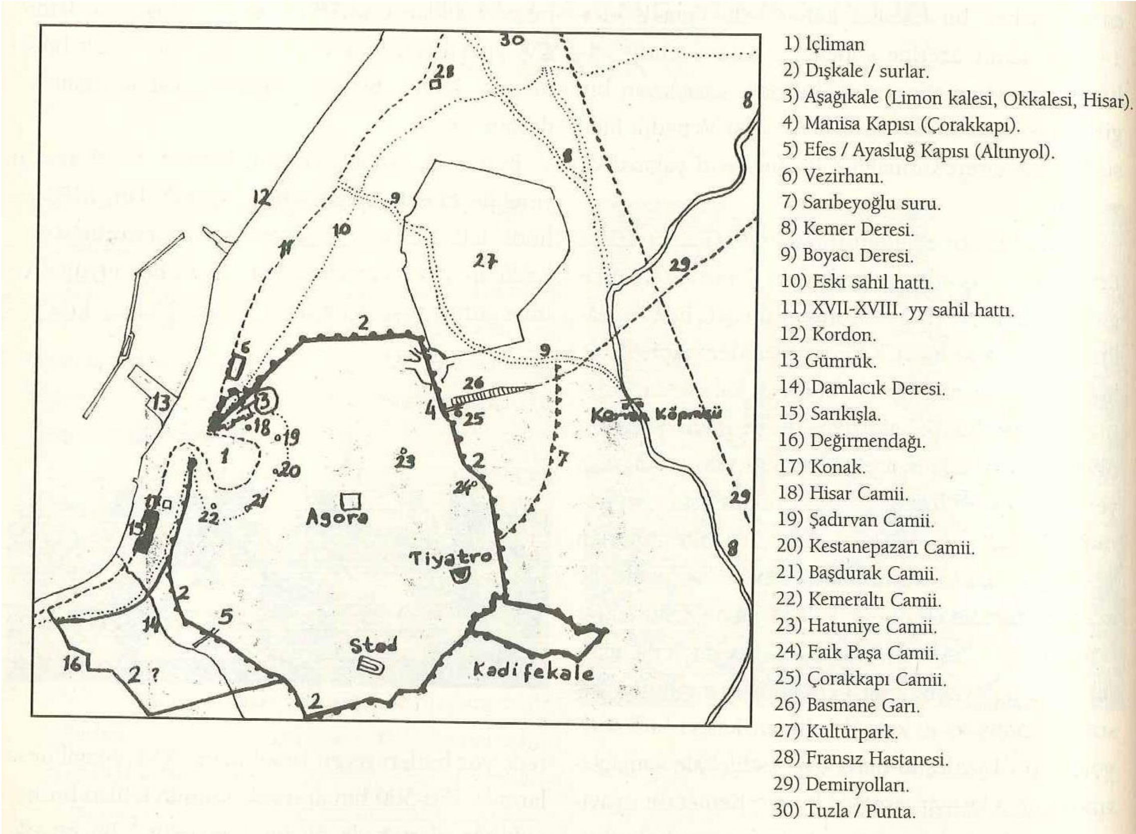


Figure 59: Historical city plan of İzmir.
(Source: Yetkin and Yılmaz, 2003a)

4.2. Historical Water Structures in the Region

Water is sacred in terms of living since the ancient times. It is also defined in different religions as the most important material of the world and the source of life. In this concept, people preferred to settle close to water sources and constructed water supply systems in order to continue their life and benefit from the sacredness of water. However, water and water supply systems became one of the most significant reasons for wars and water could create a natural disaster for those people living around. Therefore, some societies had to settle far from water supply and need to carry water to use it (Önge, 1997, p. 1 – 3). From the ancient times onwards, different water supply systems were built to fulfil the needs of human beings. These systems are conceptually based on various usage necessities such as directly using, storing and carrying water. The traditional directly usage water supply systems are fountains, kiosks (*sebil*) and *şadırvan*. The water supply systems as storage units are the cisterns. The carrying water supply systems are the long-distance water conveyance systems (aqueducts). All of these systems are connected to each other to fulfil the needs. The water carried with aqueducts are stored in cisterns and transmitted to the fountains, public fountains (*sebil*) and *şadırvan* (Figure 60) (Ürer, 2013, p. 186).

The aqueducts are important headwork, because they provide water to all other water structures and save people to carry water manually from long distances.

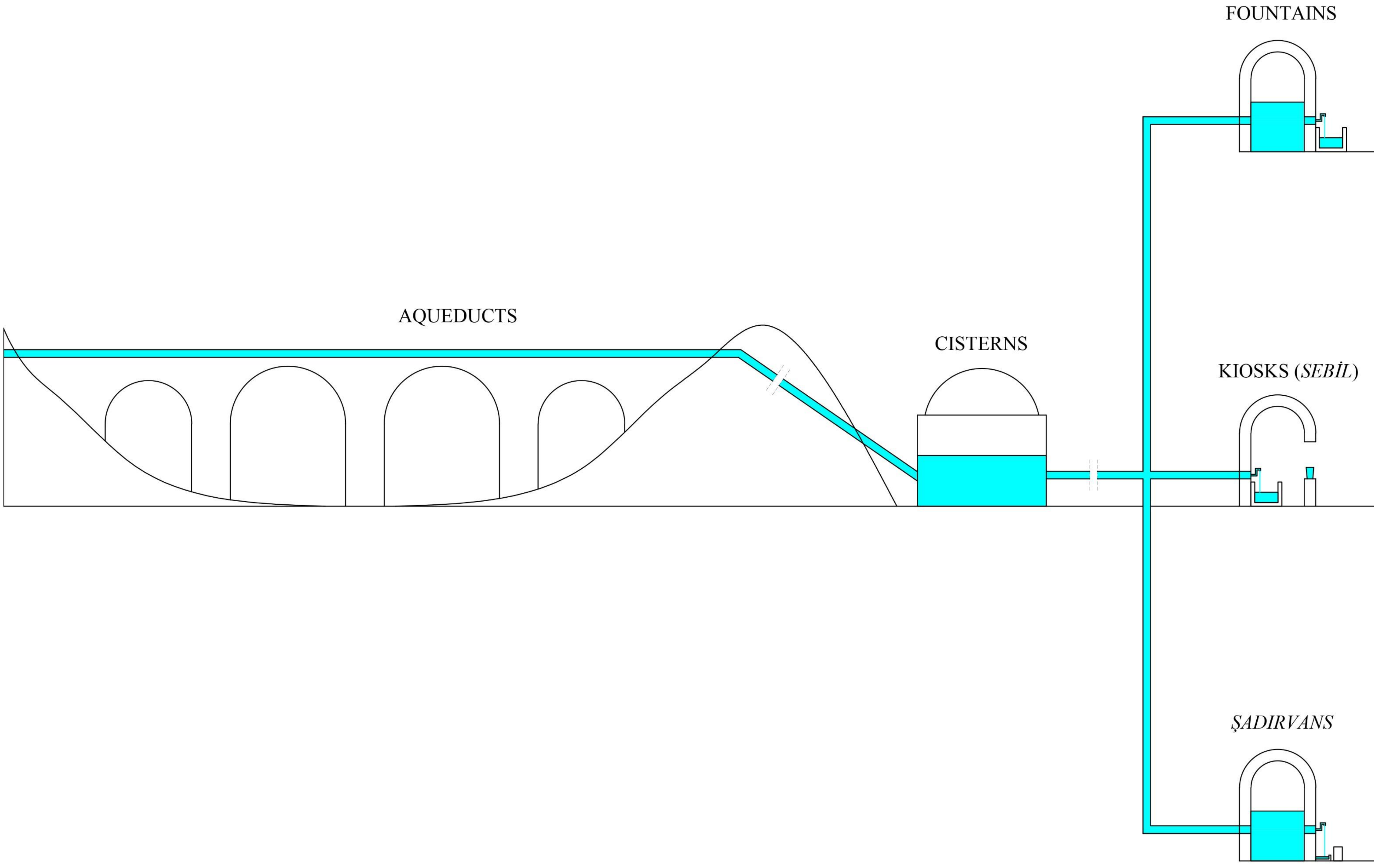


Figure 60. The process of carrying, storing and using water by water structures.

4.2.1. Fountains, Public Fountains (*Sebil*), *Şadırvans* in İzmir

The systems providing usage water directly are identified in the below.

4.2.1.1. Fountains

Çeşme, fountain in English, comes from Persian defines 'water from a hole like an eye (*göz*)'. Historical fountains are public structures to provide water for all of the people living in an era. They emphasize the significance of water in an era when usage water was not running in each housing unit. They are gathering points for people and develop the idea of sharing. Fountains are categorized under four headings according to their locations and purpose. These are private fountains (*hususi çeşmeler*), general fountains (*umumi çeşmeler*), square fountains (*meydan çeşmeleri*) and fountains with *sebil* (*sebilli çeşmeler*) (Geyik, 2007; Önge, 1997).

Fountains have five parts; water tank (*su haznesi*), faucet stone or panel stone (*musluk taşı* or *ayna taşı*), inscription panel (*kitabe*), basin of water (*su teknesi* or *kurna*) and waiting platforms (*bekleme sekileri*) (Geyik, 2007, p. 10).

In İzmir and close environment there are seventy-eight historical fountains under different categories. Nineteen of them are in religious and social buildings. Thirteen of them are fountains of khans, madrasahs, squares and districts. Thirty-eight of them are nameless and called with the names of their neighborhoods. Eight of the fountains have not reached today (Geyik, 2007; Ürer, 2013).

Table 9. Locations and construction dates of historical fountains in İzmir.

Location	**Construction Date**								
	14th	**15th**	**16th**	**17th**	**18th**	**19th**	**20th**	**Unknown**	**Total**
Religious and social buildings	-	2	1	2	7	6	1	-	19
Khans, madrasahs, squares and districts	1	1	1	2	1	6	1	-	13
Neighborhoods	-	-	1	1	13	14	3	6	38
Not reached today	1	-	-	-	1	4	1	1	8
Total									**78**

4.2.1.2. Kiosks (*Sebil*)

Kiosks (*sebil*) have been used as charities in water architecture. *Sebil* means ‘road’ in Arabic. In Turkish it had the meaning of the road of goodness and charity. In the cities, kiosks (*sebil*) was built to supply free and clean water for the people passing through from the road. They are special to Turkish architectural characteristics. Kiosks (*sebil*) are named under four headings according to their locations. They are corner kiosks (*köşe sebilleri*), façade kiosks (*cephe sebilleri*), window kiosks (*pencere sebilleri*) and monumental, square or with fountain kiosks (*abidevi sebiller, meydan sebilleri* or *çeşmeli sebiller*) (Geyik, 2007; Önge, 1997).

Table 10. Locations of historical kiosks (*sebil*) in İzmir.

Location	**Numbers of Kiosks (*Sebil*)**
Corner kiosks (*köşe sebilleri*)	3
Façade kiosks (*cephe sebilleri*)	11
Window kiosks (*pencere sebilleri*)	2
Monumental kiosks (*abidevi sebiller)*	1
The kiosks whose type is unknown	6
Total	**23**

There are twenty two kiosks (*sebil*) in İzmir. However, only eight of them have reached today (Ürer, 2013, p. 219 - 226).

Table 11. Existances and construction dates of historical kiosks (*sebil*) in İzmir.

Existance	**Constrution Date**			
	18th	**19th**	**Unknown**	**Total**
Reached today	3	5	-	8
Not reached today	9	4	2	15
Total				**23**

4.2.1.3. *Şadırvans*

Şadırvan means 'flows more' in Persian. *Şadırvans* are fountains, located in the courtyards of mosques, khans and madrasahs for ablution prior to praying. *Şadırvans* have for different categories according to their architectural characteristics; *şadırvans* with different tank forms, *şadırvans* whose superstructure is reinforced with double supports (*üst örtüsü çift destek sırası ile taşınan abdest şadırvanları*), water distribution and ventilation system in the courtyards of mosques and basket *şadırvans* (*zembil şadırvanları*) (Geyik, 2007; Önge, 1997).

There are sixteen *şadırvans* in İzmir today (Geyik, 2007, p. 18 - 19).

Table 12. Locations and construction dates of *şadırvans* in İzmir.

Location	**Construction Date**					
	15th	**16th**	**17th**	**18th**	**19th**	**Total**
Mosque *Şadırvans*	2	4	-	1	7	14
Şadırvans with monumental building	-	-	1	-	-	1
Square *Şadırvans*	-	-	-	-	1	1
Total						**16**

4.2.2. Cisterns in İzmir

Cisterns are the rain water storages linking to the water conveyance systems for systematic distribution of water of the settlements. Six of the historical cisterns that have reached today are located in and around Kadifekale (Ürer, 2013, p. 188). It can be said that the cisterns were built in 1225 by Emperor Johan Ducas Vatatzes as it is written on an inscription (C. I. Gr. IV, 3749) (Weber, 1899).

4.2.3. Water Conveyance Systems in İzmir

Apart from Vezirağa Aqueduct, there are five historical long-distance water conveyance systems in İzmir. Only four of them have reached today; namely Karapınar Waterline (remains), Akpınar Waterline (remains), Kapancıoğlu Waterline (only pipes), and Osmanağa (Kozağaç, Kızılçullu) Waterline. Buca Waterline couldn't reach today (Figure 61 and 62). All of them are based on the idea of carrying water from the high levels of the city to the center (Ürer, 2013, p. 188). Two of the aqueducts were constructed in 17th century (Vezirağa Waterline and Osmanağa Waterline). The construction dates of others are not clearly stated in the sources. However, their construction techniques composed of rubble stone and brick in random order point out the characteristics of Byzantine era. Karapınar Waterline and Kadifekale Cistern which dates to 1225 work together (Figure 64). Laflı (2011) interpretes the historical aqueducts of İzmir as late antique monuments.

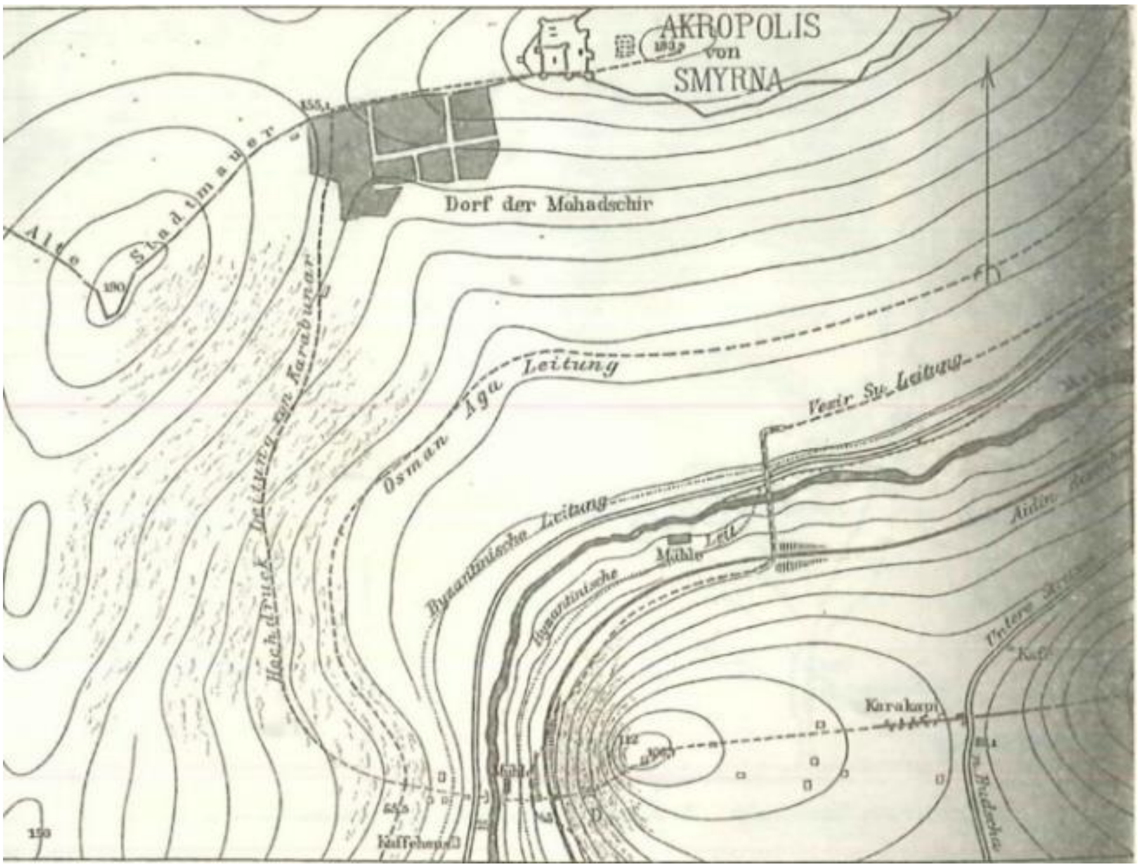
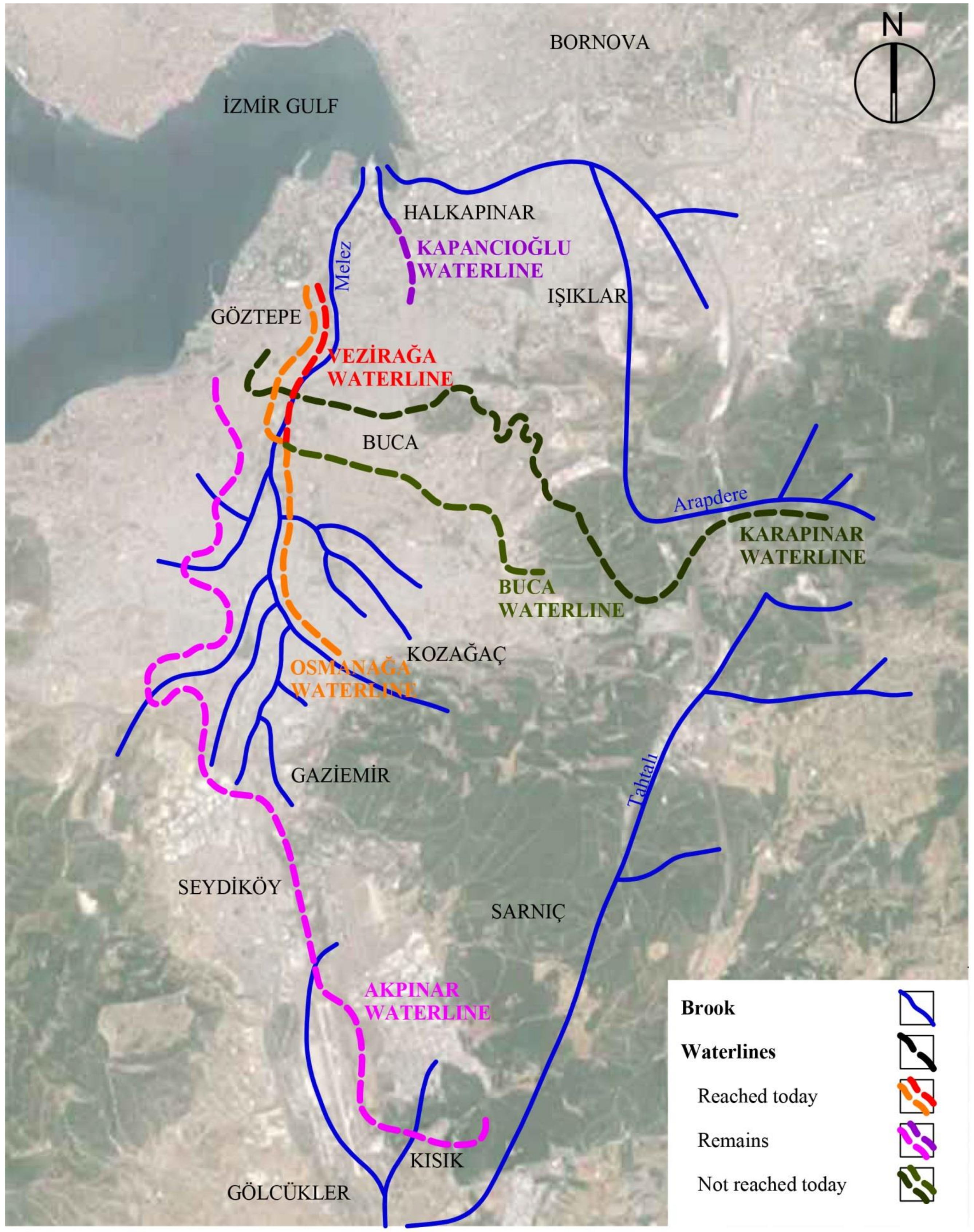
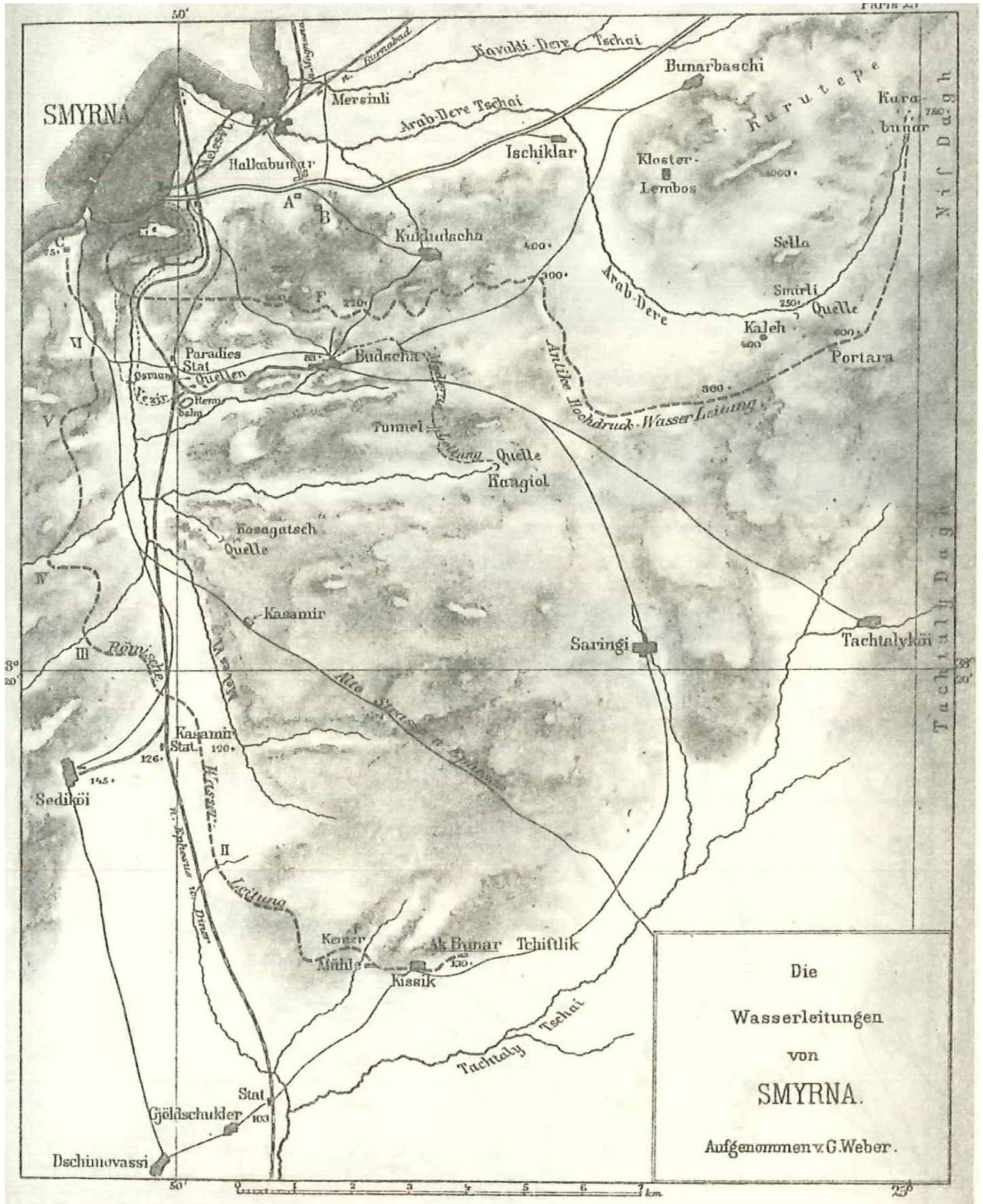


Figure 61. Weber's map showing the waterlines around Buca and Kadifekale.
(Source: Weber, 1899)



The map showing the location of waterlines and brooks in the area
(Revised from Weber,1898 and Öziş, et al., 1999)



Weber's map showing waterlines in İzmir
(Weber,1898)

Figure 62. The waterlines map of the study area.

4.2.3.1. Karapınar Waterline

The Karapınar Waterline is 30 km long ancient water conveyance system carrying water from Karapınar springs, in upper parts of Arapdere creek, at the south of Nif Mountain to Kadifekale. It passes Melez valley with stone pipes and high pressure system (*ters sifon etkisi*) (Figure 63 and 64). The stone pipes were passed over an arched aqueduct on Melez valley with 26 m height to reach Kadifekale. The numbers of stone pipes were defined as 58 by Weber (1899) (Figure 65 and 66). When the average diameter of the stone pipes and the length of the waterline were taken into consideration the number should be around 6000 pipes. However, any researcher couldn’t have the information of all the pipes around. (Weber, 1899; Ürer, 2013; Öziş, et.al, 1999).

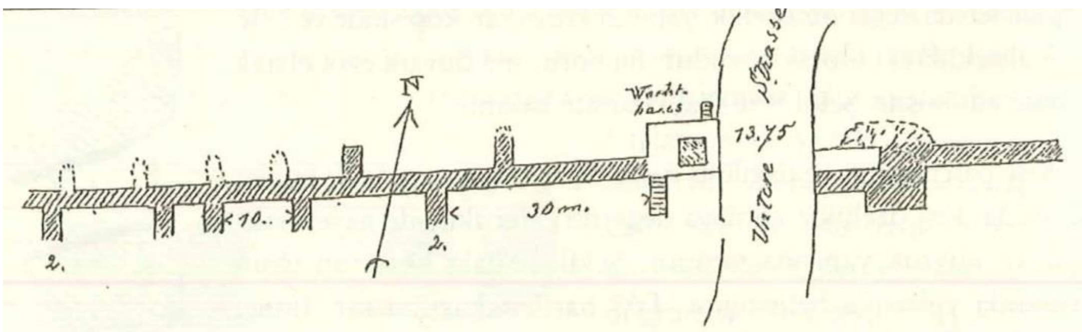


Figure 63. The plan of Weber showing the part of Karapınar Waterline where the waterline reached to Kadifekale (Source: Weber, 1899)

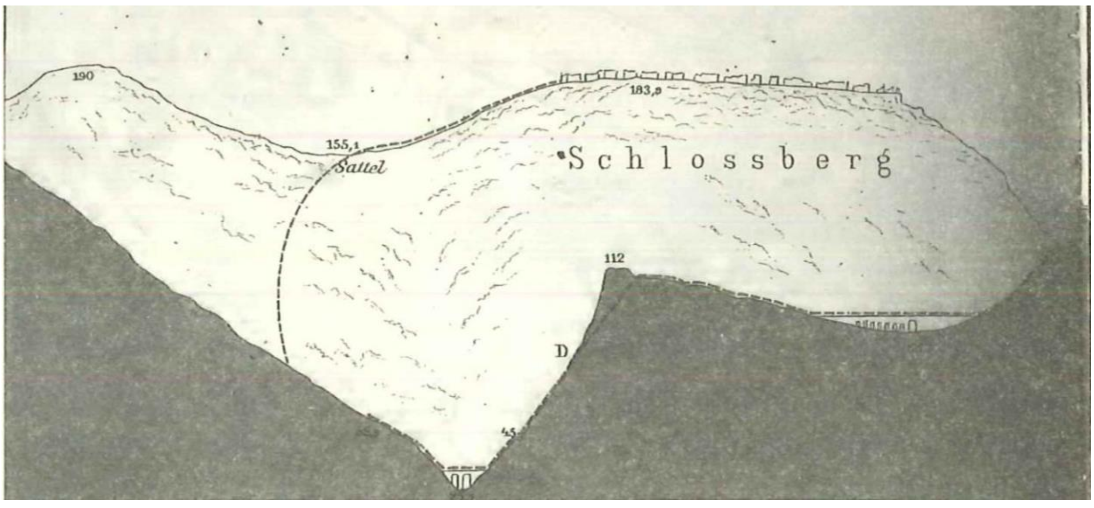


Figure 64. Weber’s section showing the high pressure system to Kadifekale. (Source: Weber, 1899)

Figure 65. The remains of pipes of Karapınar Waterline.
(Source: Öziş, et al., 1999)

Figure 66. The remains of the arches of Karapınar Waterline which passes Emres Brook. (Source: Öziş, et al., 1999)

4.2.3.2. Akpınar Waterline

The Akpınar Waterline was the ancient water conveyance system carrying water from the Akpınar springs in Kısıkköy to the Temple of Zeus at the south-west of Kemeraltı. According to the traces, the waterline is 27 km long and included six aqueducts. Today most of the waterline has lots of damages and is the oldest waterline of İzmir (Weber, 1899; Ürer, 2013).

The first aqueduct was on a valley which is 2 km away from the first point of waterline. It is straight wall which is around 160 m long. The middle of the aqueduct was around 25 m and it is demolished today. The width of the aqueduct is 1.80 m. The aqueduct was constructed with rubble and rough cut stone. The sea level difference was used in this system to carry water (Figure 67) (Weber, 1899; Ürer, 2013).

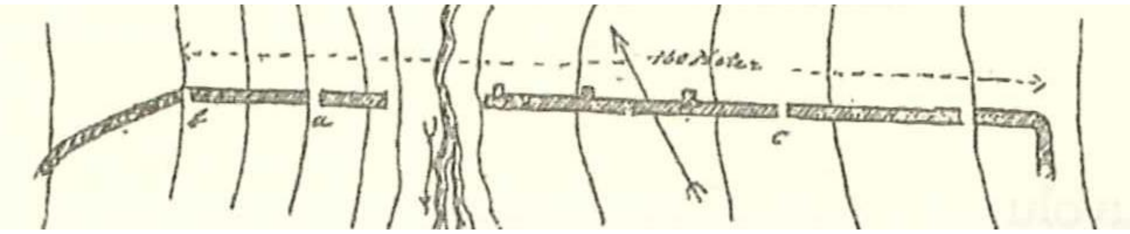


Figure 67. The plan of Weber showing the first aqueduct of Akpınar Waterline.
(Source: Weber, 1899)

The second trace is some wall remains close to the Gaziemir Station. The remains show that this part of the waterline was a canal with a wall which turns around the station underground (Figure 68). According to Weber, the canal clashed with the railway however only the road between the 110 m and 115 m could be examined because of the manmade fields (Weber, 1899).

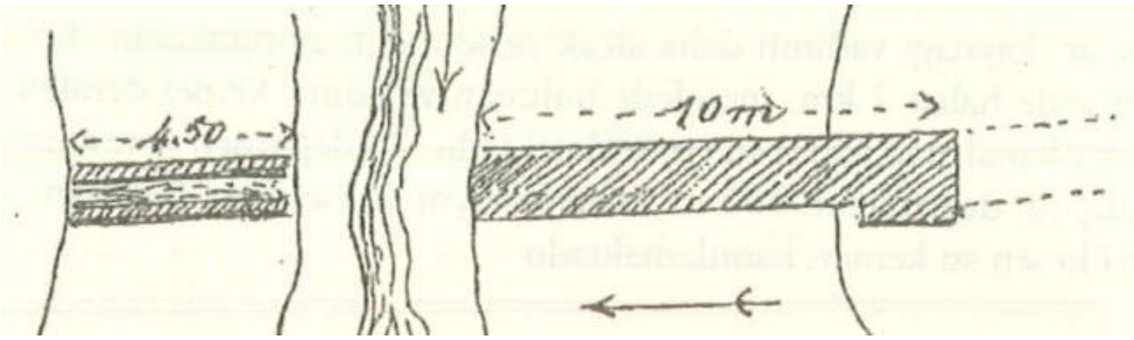


Figure 68. The plan of Weber showing the second aqueduct of Akpınar Waterline.
(Source: Weber, 1899)

Around Seydiköy there was found another valley with 135 m long and 12 m high aqueduct (Figure 69). The construction technique of this aqueduct was similar to the first aqueduct. There was a sustaining wall crossing the aqueduct to support it against the rains. The arc of this aqueduct collapsed, only the traces could be seen (Weber, 1899).

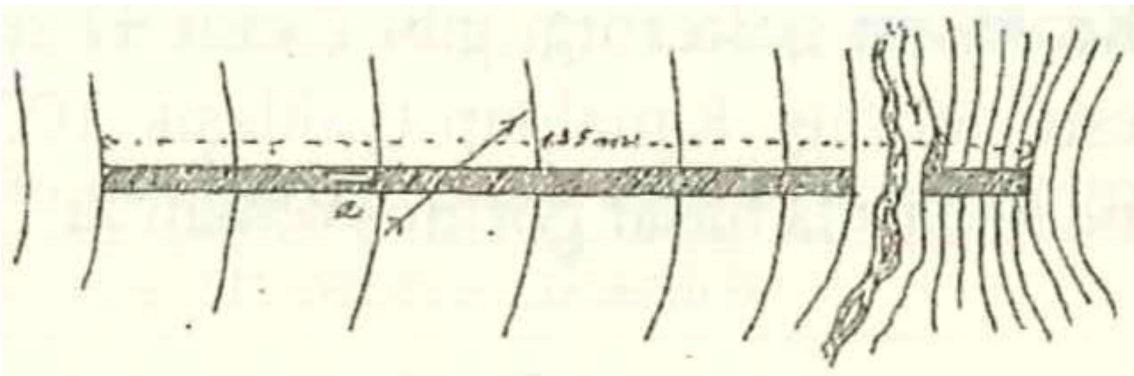


Figure 69. The plan of Weber showing the third aqueduct of Akpınar Waterline.
(Source: Weber, 1899)

Through the north there was the fourth aqueduct of the waterline (Figure 70). It was supported by buttresses. The information comes from the traces of buttresses which constructed with cut stone and lime. This aqueduct was demolished from lots of pieces and it lost its arches. However, the walls with cut stone and lime were still seen on the site (Weber, 1899).

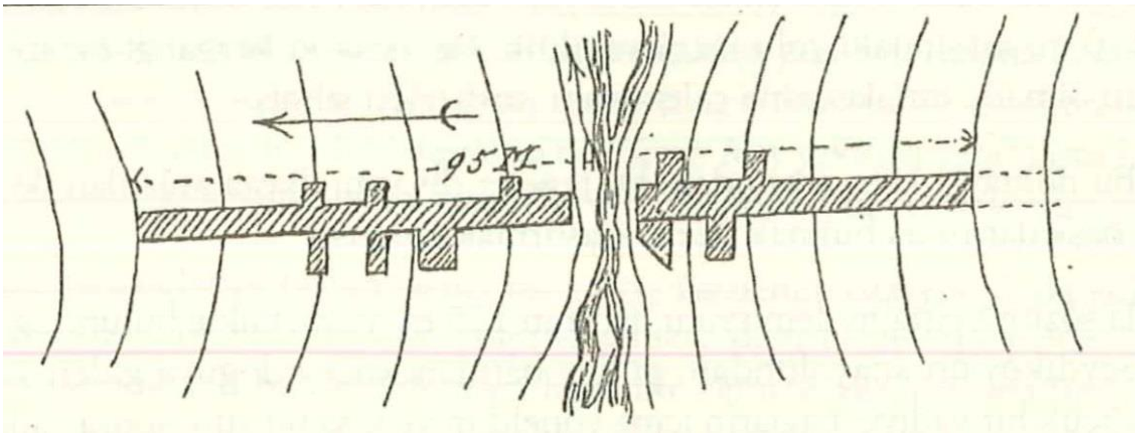


Figure 70. The plan of Weber showing the fourth aqueduct of Akpınar Waterline.
(Source: Weber, 1899)

There was fifth aqueduct around Bozyaka on the waterline (Figure 71). The new aqueduct had the same construction technique with the first one again. It was 70 m long and in 5 m height from the brook. The aqueduct lost its arch on the brook as it happen to all other aqueducts on this waterline (Weber, 1899).

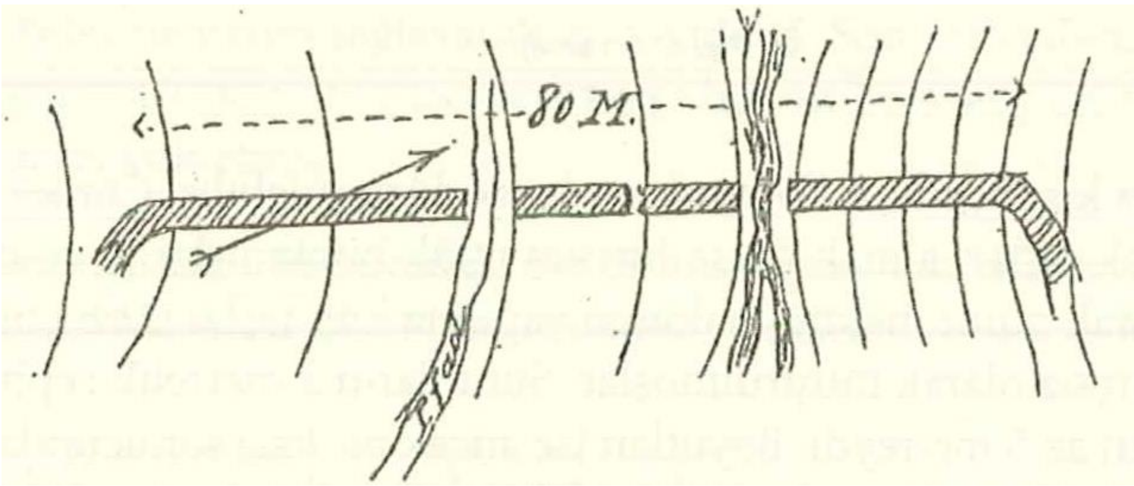


Figure 71. The plan of Weber showing the fifth aqueduct of Akpınar Waterline.
(Source: Weber, 1899)

The sixth aqueduct of the waterline is located on plateau, between the Melez valley and the south of the city. As a construction tecnique, this aqueduct has some difference from the others. The aqueduct has a series of columns which connected to each other with lower walls as seen in plan (Figure 72). The material is also different. In the aqueduct, travertaine used as material (Weber, 1899).

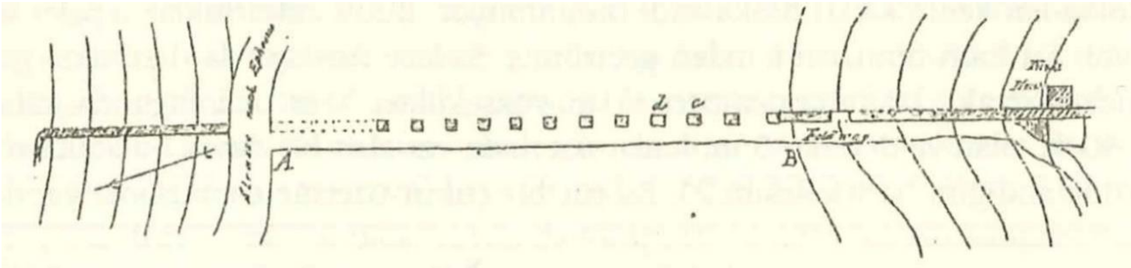


Figure 72. The plan of Weber showing the fifth aqueduct of Akpınar Waterline.
(Source: Weber, 1899)

Figure 73. The side wall remains of an aqueduct on Akpınar Waterline.
(Source: Öziş, et al., 1999)

Figure 74. The side wall remains of an aqueduct on Akpınar Waterline.
(Source: Öziş, et al., 1999)

4.2.3.3. Buca Waterline

Buca Waterline is a lost water conveyance system carrying the spring waters of Kanlıgöl district to İzmir. It dates back to Byzantine period. It carried water to the Karapınar System and Osmanağa System with two lines of terracotta pipes. There are Şirinyer Aqueducts (Figure 75) which pass Melez valley from 100 m east of Vezirağa Aqueduct. It is thought that Vezirağa Aqueduct replaced these two Sirinyer Aqueducts. However, further investigations and excavations should be carried out to understand its characteristics (Weber, 1899; Ürer, 2013).

Figure 75. Two aqueuducts on Osmanağa Waterline and Karapınar Waterline which make Buca Waterline pipes pass Melez valley, the closer arch showing the upstream. (Source: Öziş, et al., 1999)

4.2.3.4. Kapancıoğlu Waterline

Kapancıoğlu Waterline is a short water conveyance system, carrying water of Diana Bath in Halkapınar to Kapancıoğlu Fountain at the north of Buca. There are some traces stone pipes from Caravan Bridge to the garden at the east of Tepecik. The pipe types of the waterline are in accordance with Roman period. The waterline had some damages and became a shorter waterline. However, with all damages, it used to provide water to the Kapancıoğlu Fountain until the 19th century (Weber, 1899; Ürer, 2013).

4.2.3.5. Osmanağa (Kozağaç, Kızılçullu) Waterline

It is thought that the water of Osmanağa Waterline comes from Kozağaç Brook or from another source in Buca (Öziş, et al., 2008). Another source states that water comes from Buca plain in Büyük and Küçük Paradiso slope and passes from Kızılçullu

Aqueduct to reach the center of the city (Figure 77) (Weber, 1899). It is thought that it was built after Veziraǧa Aqueduct by Osman Aǧa who repaired the Kızılçullu Aqueduct and built twenty fountains and gave his name to the system. The system was composed of two aqueducts (Figure 76); 50 m and 120 m in length, respectively. The long aqueduct has two arches at its bottom used as footings and 14 arches at its top. The arches have different sizes, while largests are at the center. This variation is in accordance with the form of the valley. The aqueduct is constructed with rubble and rough cut stone. The characteristics of the long one are in line with Roman period (Weber, 1899; Ürer, 2013).

Figure 76. Two aqueducts of Osmanaǧa Waterline.
(Source: Tanış, c2013)

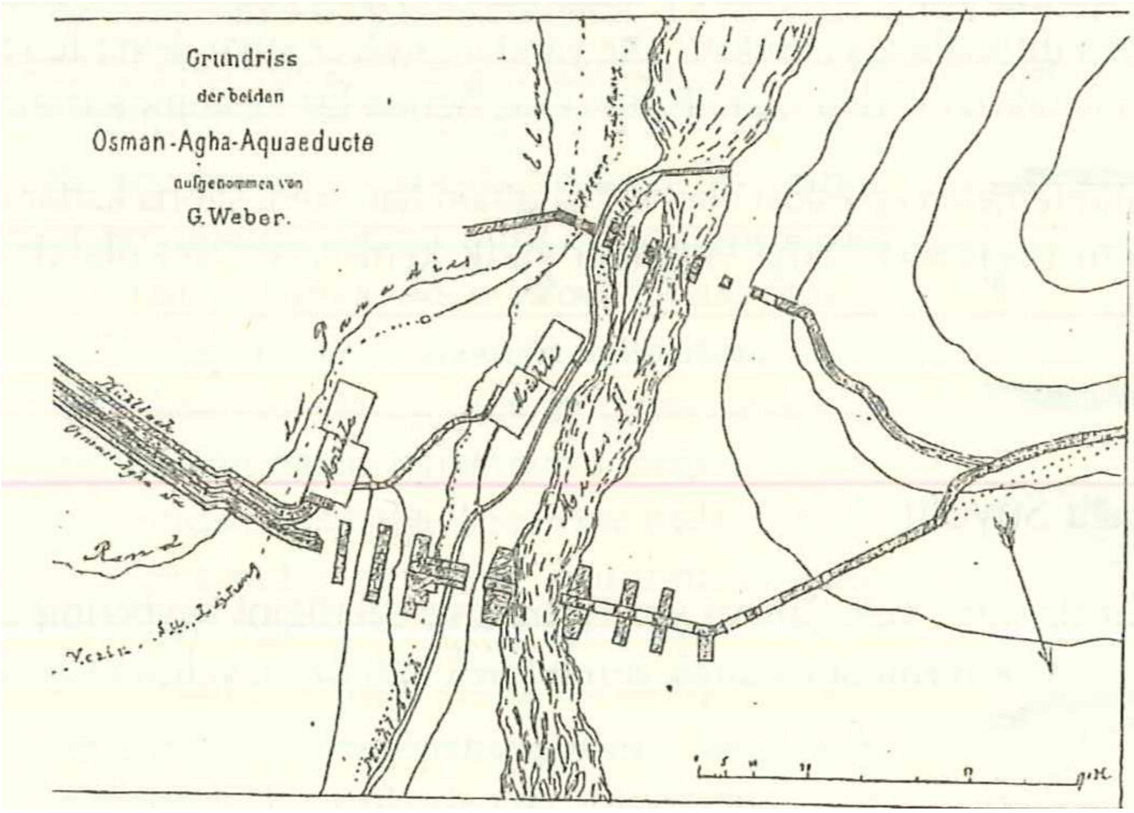


Figure 77. The plan of Weber showing the aqueduct on Osmanağa Waterline.
(Source: Weber, 1899)

4.3. Comparative Study with Similar Examples From Ottoman Period (16th, 17th, and 18th Century)

The comparative study with similar examples from Ottoman Period is to understand the general layout of the aqueducts on that period and the historical value of Vezirağa Aqueduct on that period. In order to make this evaluation ten aqueducts is chosen according to their period, materials, type of arches, construction techniques and current conditions. The general characteristics of aqueducts are defined under ten subjects (Table 14). The water conveyance system defines that the water comes from which location and goes to where (Table 14). Position locates the aqueduct on the map. Dimension gives the information of the width, length and height of the aqueduct. The form of aqueduct could change according to the valley or site that it passed. Therefore, form should be defined detailly. Arch series, arch profile and double arch columns define the arch characteristics and the arch form of the aqueduct. Buttresses column shows that if the aqueduct had needed any support from sides for any reason such as out of plumbness, high water pressure. Stone duct and material define the material characteristics of the aqueduct.

Table 13. The general characteristics of compared examples from Ottoman Period (16th, 17th and 18th century).

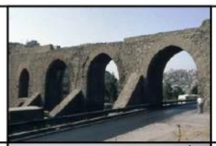
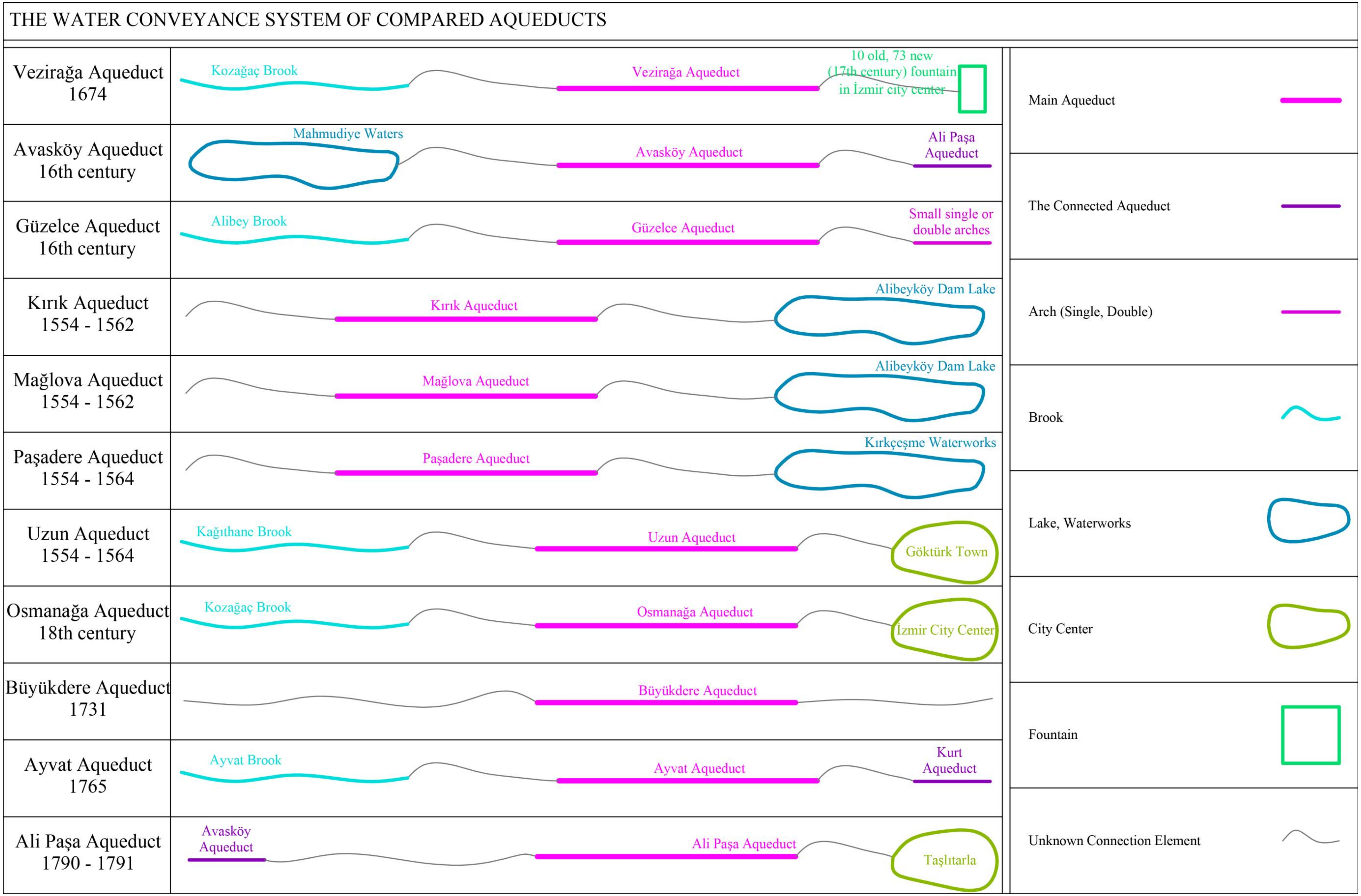
COMPARATIVE STUDY WITH SIMILAR EXAMPLES FROM OTTOMAN PERIOD (16th, 17th and 18th century)											
Building Elements / Aqueduct Examples	Photographs	Water Conveyance System	Position	Dimensions (w x l x h m)	Form	Arch Series	Arch Profile	Double Arch	Buttresses	Stone Duct	Material
Vezirağa Aqueduct 1674		Kozağaç Brook Vezirağa 10 old, 73 new fountain	Melez Valley İzmir	1.70 x 165 x 13	Linear	●	Depressed Arch	●	●	●	Rubble Stone Brick
Avasköy Aqueduct 16th century		Mahmudiye waters Avasköy Ali Paşa Aqueduct	Atışalanı İstanbul	1.5 x 158.2 x 8.2	Linear	●	Depressed Arch	-	●	●	Cut Stone
Güzelce Aqueduct 16th century		Alibey Brook Güzelce Small single or double arches	Alibey Brook İstanbul	2.6 x 155 x 29.5	Linear	●	Depressed Arch	●	●	●	Cut Stone
Kırık Aqueduct 1554 - 1562		Kırık Aqueducts on Alibeyköy dam lake	Kemerburgaz İstanbul	- x 408 x 35	L Shaped	●	Semi-circular Arch	●	●	●	Cut Stone
Mağlova Aqueduct 1554 - 1562		Mağlova Alibeyköy dam lake (located)	Alibey Brook Valley İstanbul	- x 257 x 36	Linear	●	Depressed Arch	●	●	●	Cut Stone
Paşadere Aqueduct 1554 - 1564		Paşadere Kırkçeşme waterworks (used by)	Kemerburgaz İstanbul	- x 102 x -	Linear	●	Semi-circular Arch	●	●	●	Cut Stone
Uzun Aqueduct 1554 - 1564		Kağıthane Brook Uzun Göktürk town	Kağıthane Brook İstanbul	- x 710 x 26	Linear	●	Semi-circular Arch	●	●	●	Cut Stone Rubble Stone
Osmanağa Aqueduct 18th century		Kozağaç Brook Osmanağa City center	Melez Valley İzmir	- x 120 x -	Linear	●	Depressed Arch	●	●	●	Rubble Stone Brick
Büyükdere Aqueduct 1731		-	İstanbul	-	Linear	●	Depressed Arch	-	●	-	-
Ayvat Aqueduct 1765		Ayvat Brook Ayvat Kurt Aqueduct	Ayvat Brook İstanbul	- x 63 x 13.4	Linear	●	Depressed Arch	-	●	-	Rubble Stone
Ali Paşa Aqueduct 1790 - 1791		Avasköy Aqueduct Ali Paşa Taşlıtarla	Bayrampaşa İstanbul	-	Linear	●	Depressed Arch	●	●	-	Cut Stone

Table 14. The water conveyance systems of compared aqueducts.



Vezirağa Aqueduct is compared with ten examples. Nine of them are in İstanbul and one in İzmir.

Most of them (6/11; Avasköy Aqueduct, Güzelce Aqueduct, Kırık Aqueduct, Mağlova Aqueduct, Paşadere Aqueduct, and Uzun Aqueduct) belong to 16th century. Two of them (2/11; Vezirağa Aqueduct and Osmanağa Aqueduct) belongs to 17th century. Three of them (3/11; Büyükdere Aqueduct, Ayvat Aqueduct, and Ali Paşa Aqueduct) belong to 18th century.

Four of the aqueducts (4/11; Vezirağa Aqueduct, Avasköy Aqueduct, Güzelce Aqueduct, and Ayvat Aqueduct) were carrying waters of a brook or lake to another architectural monument. Three of them (3/11; Uzun Aqueduct, Osmanağa Aqueduct, and Ali Paşa Aqueduct) were carrying waters of a brook to towns or cities. Three of ten (3/11; Kırık Aqueduct, Mağlova Aqueduct, and Paşadere Aqueduct) were taking waters from an unknown source to a dam lake. Only one of them (1/11; Büyükdere Aqueduct) is in a water conveyance system with no information.

Most of the compared aqueducts (10/11; Vezirağa Aqueduct, Avasköy Aqueduct, Güzelce Aqueduct, Mağlova Aqueduct, Paşadere Aqueduct, Uzun Aqueduct, Osmanağa Aqueduct, Büyükdere Aqueduct, Ayvat Aqueduct, and Ali Paşa Aqueduct) are linear in form while Kırık Aqueduct is L shaped related with the site characteristics.

Figure 78. Kırık Aqueduct.
(Source: Mimar Sinan Eserleri, 2012)

All of the aqueducts have arch series. Most of them (8/11; Vezirağa Aqueduct, Avasköy Aqueduct, Güzelce Aqueduct, Mağlova Aqueduct, Osmanağa Aqueduct, Büyükdere Aqueduct, Ayvat Aqueduct, and Ali Paşa Aqueduct) have depressed arches. Three of them (3/11; Kırık Aqueduct, Paşadere Aqueduct, and Uzun Aqueduct) were constructed with semi-circular arches. Eight of them (8/11; Vezirağa Aqueduct, Güzelce Aqueduct, Kırık Aqueduct, Mağlova Aqueduct, Paşadere Aqueduct, Uzun Aqueduct, Osmanağa Aqueduct, and Ali Paşa Aqueduct) have double arches.

Figure 79. Mağlova Aqueduct with its arch series.
(Source: Mimar Sinan Eserleri, 2012)

Three of the compared aqueducts (3/11; Büyükdere Aqueduct, Ayvat Aqueduct, and Ali Paşa Aqueduct) do not have stone duct while seven of them have.

All of the İstanbul examples (9/11; Avasköy Aqueduct, Güzelce Aqueduct, Kırık Aqueduct, Mağlova Aqueduct, Paşadere Aqueduct, Uzun Aqueduct, Büyükdere Aqueduct, Ayvat Aqueduct, and Ali Paşa Aqueduct) are constructed out of cut stone in both walls and arches, while İzmir ones (2/11; Vezirağa Aqueduct and Osmanağa Aqueduct) is out of rubble stone reinforced with reused cut stone in the walls and brick in the arches.

Six of the compared aqueducts (6/11; Avasköy Aqueduct, Güzelce Aqueduct, Kırık Aqueduct, Mağlova Aqueduct, Paşadere Aqueduct, and Uzun Aqueduct) was designed by Mimar Sinan. Three of them (3/11; Vezirağa Aqueduct, Osmanağa Aqueduct and Büyükdere Aqueduct) have the information about who gave the order for construction. The designers of four of them (4/11; Osmanağa Aqueduct, Büyükdere Aqueduct, Ayvat Aqueduct, and Ali Paşa Aqueduct) are unknown today.

CHAPTER 5

PERIOD ANALYSIS AND RESTITUTION OF THE AQUEDUCT

Vezirağa Aqueduct had some changes since the construction date. The additions and losses of the structure are described in this section with their dates. Besides, with information coming from period analysis the second period of the aqueduct is presented.

5.1. Period Analysis

Vezirağa Aqueduct has six periods from the 4th century BC to present according to different sources and the site observations (Appendix F1 and F2).

The first period is the construction of the first aqueduct at the same location with the present one in the 4th century BC. This date is not certain according to Pococke (1730) and Storari (1857), and Weber does not accept this construction date (1899). Pococke claimed that the ancient stones under the abutments and the construction characteristics of these levels were the proofs of an old water conveyance system.

The second period is the construction of the Vezirağa Aqueduct by Köprülü Fazıl Ahmet Paşa in 1674 (Ürer, 2013). It was built in two stories composed of four arches at the bottom and nine arches at the top and 160 m in length. (Appendix F2).

Figure 80. An old photograph showing west facade of Vezirağa Aqueduct taken by a levantine Rubellin. (Source: Laflı, 2011)

The third period is the construction of the buttresses on the eastern façade. According to the site observations and Georg Weber's interpretations, these buttresses were added to the wall just after its construction. However, Ergün Laflı presents an old photograph of the east façade without butresses. He states that this photo dates to 20th century (Figure 81). But there is another photo with butresses and dated 1890 (Figure 82). The exact date of the addition cannot be stated, but it should be before 1890.

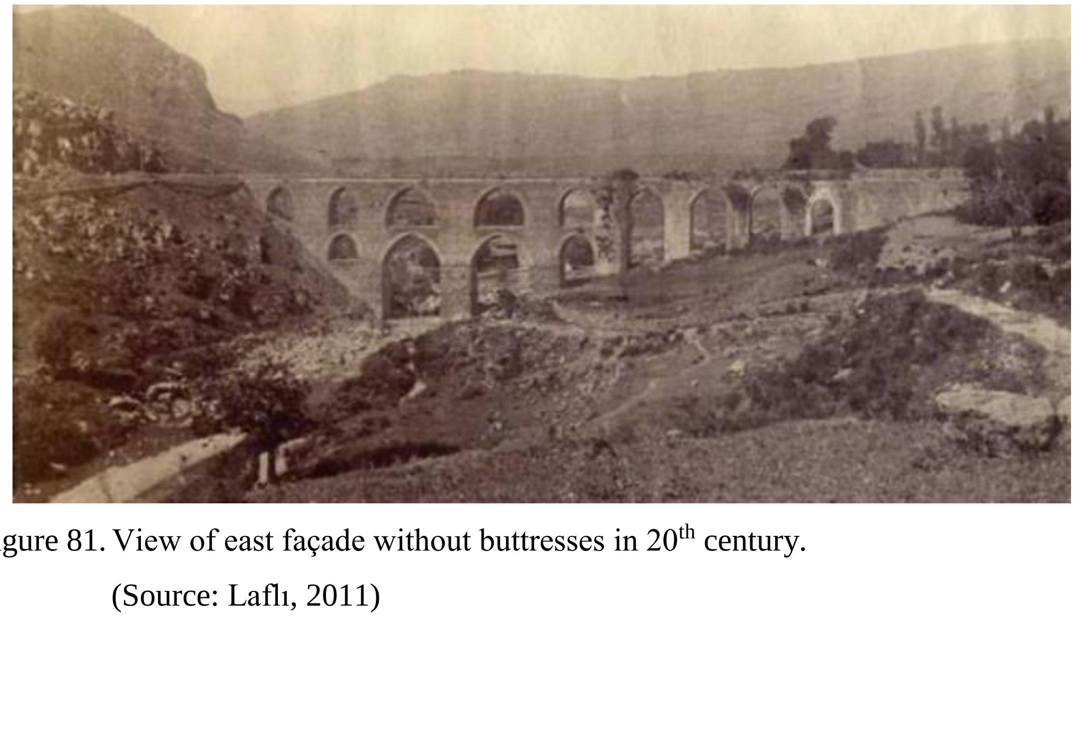


Figure 81. View of east façade without buttresses in 20th century. (Source: Laflı, 2011)

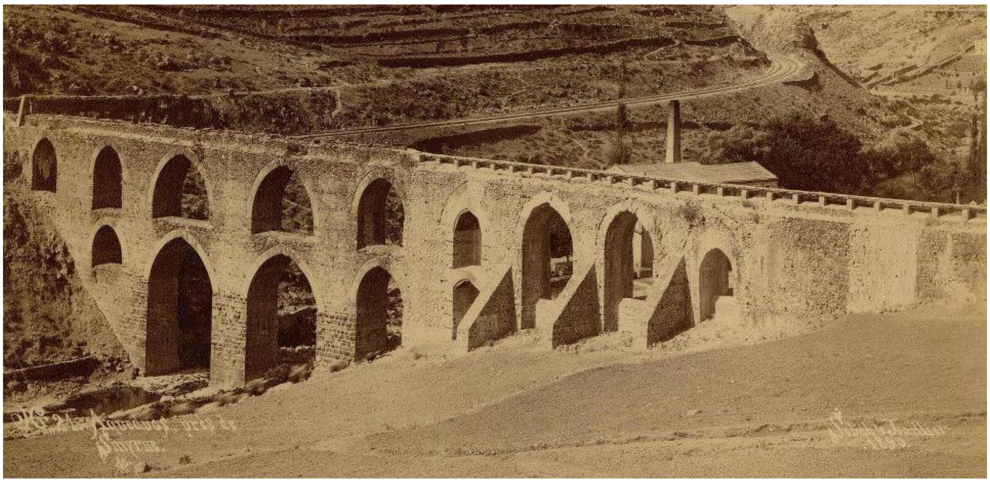


Figure 82. View of east façade with buttresses in 1890.
(Source: İzmir Metropolitan Municipality, c2015)

The fourth period is the addition of a supportive arch to the fourth arch from the northern end. Georg Weber stated that the aqueduct was repaired around 1870s and to solve the structural problems of the forth arch from the northern end, an additional arch was constructed under the original arch. Furthermore, in 1866, the İzmir-Aydın railway was constructed. The railway is passing through the south end of the aqueduct. The demolishment between wall portions B and C had occurred on that date (Appendix F2).

Figure 83. An old photo showing east facade in 1909.

(Source: İzmir Metropolitan Municipality, c2015)

Figure 84. An old photo showing west facade.
(Source: İzmir Metropolitan Municipality, c2015)

The fifth period is the demolishment of most of the arches. In a photo dated 1919 (Figure 85), the aqueduct is seen as a whole. The arches in the center collapsed in a spate in 1931 (Akyüz Levi, 2009, p. 161). In the demolishment, the aqueduct lost four of its bottom arches and four of its top arches at its center (Appendix F2).

Figure 85. View of the east facade in 1919.
(Source: Yetkin and Yılmaz, 2003b, p. 234)

The sixth period is the construction of the concrete duct and addition of the iron reinforcements to the southern and of wall portion A. Some parts of the stone duct were covered with concrete. However, the concrete duct was not completed in this repair. The iron reinforcements were added to support the remains of original arches at the southern end of wall portion A. However, the dates of these applications are not known exactly.

5.2. Restitution of the Aqueduct

The sources of the restitution should be defined to illuminate the restitution problems. The reliability degrees of the source are to be presented to guide the intervention decisions.

5.2.1. Restitution Problems

The restitution problems are prioritized below;

- The demolished part between wall portions A and B
- Remains of original arches at the south end of wall portion A and north end of wall portion B
- The demolished part on the railway
- The repaired brick – stone masonry arches on the south end of wall portion A
- Nonexistence of buttresses on wall portion A
- The demolished stone duct
- The arch on wall portion B

5.2.2. Restitution

After the identification of the restitution problems, the restitution solutions are formulated by the help of the sources and their reliability degrees (Appendix G1).

With the first level reliable information, the remains of original arches at the south end of wall portion A and north end of wall portion B, the repaired brick – stone masonry arches on the south end of wall portion A, and the arch on wall portion B are drawn in detail.

As seen on the traces of the aqueduct, there were brick masonry arches on the top of each other at the south end of wall portion A and north end of wall portion B (Appendix G2). The forms of these arches are checked from an old photograph of the aqueduct. The top arch of wall portion B has ~ 5.80 m spanning distance and ~ 3.10 m height from springing line to the keystone. The below arch of wall portion B is thought to have some deterioration in form. However, with the help of the old photograph, the arch is formed with ~ 6.20 m spanning distance and ~ 3.80 m height from springing line to the keystone. The top arch of wall portion B has small traces coming from the building. It is ~ 2.90 m high from springing line to the keystone and its spanning distance is ~5.00 m. The below arch is constructed with ~ 5.40 m spanning distance and ~ 3.10 m in height from springing line to the keystone. All arches are composed of bricks (~ 4 x 20 cm) and mortar (~ 2 cm in thickness) as it is the same with the rest of the aqueduct.

The arch on wall portion B is still standing (Appendix G2). However, the old photograph shows that it was lower than the current situation in the first construction. In the original state, it was ~ 6.30 m in height from ground to keystone, while it is ~ 7.30 m in height in present condition.

The form of the repaired brick – stone masonry arches on the south end of wall portion A is found out with an old photograph (Appendix G2). As it is seen from the photograph, the total height of the arch was 9.30 m in the past. Besides, this part has two arches on the top of each other in present condition. However, there was only one arch in the original condition of the aqueduct.

The second level reliable information gives the original state of the demolished part between wall portion A and B, nonexistence of buttresses on wall portion A, the demolished stone duct, and the demolished part on the railway.

The demolishment of four arches of the aqueduct was caused by a spate in 1931. The old photographs and the comparative study within the aqueduct help to draw four arches in their right location, form, material, and detail (Appendix G2). As far as it is seen from the photograph, there two arches at the top and two arches at the bottom. The top and bottom arches are reflections of each other when the measurements are compared. The top arches have ~ 9.10 m spanning distances and ~ 6.20 m height from the springing line to keystone. The bottom arches are ~ 4.50 m in height from the springing line to the keystone. The spanning distance of these arches is ~ 9.10 m. The material of brick masonry arches and stone masonry arches are the same with the rest of the aqueduct.

Weber (1899) states in his travel notes that the buttresses on wall portion A were built after the construction of the aqueduct. Furthermore, it is seen explicitly during the site survey that there is no joint between the aqueduct and the buttresses. Therefore, the buttresses were not constructed in the original state of the aqueduct most probably (Appendix G2).

On the top of the aqueduct, there are remains of the original stone duct, new concrete duct, and traces of stone duct. The traces of stone duct shows that the stone duct was running all over the aqueduct. The form, material, and detail of demolished stone duct are identified by comparative study within the aqueduct (Appendix G2).

There is a demolished part on the railway, which is a wall part of wall portion C, juxtaposing the hillside. It is ~ 6.10 m in width and ~ 5.60 m in height with its stone duct. According to the comparative study within the building, it was constructed with stone (Appendix G2).

When the restitution drawings are completed, an aqueduct 165.20 m in length, 19.70 m in height at its highest point, and perforated with depressed arches whose of four at the bottom and nine at the top (Appendix G2).

CHAPTER 6

EVALUATION AND CONCLUSION

Veziraǧa Aqueduct is identified with its historical, architectural and structural characteristics in this thesis. The historical value of the aqueduct is defined by comparing it with the similar structures and also by identifying its socio-cultural significance in the history of the city of İzmir. Besides, the structural condition of the aqueduct is described to evaluate the dynamic behavior of the structure under gravitational and lateral loads.

6.1. Evaluation

The studies on Veziraǧa Aqueduct to identify historical, architectural and structural characteristics have revealed its qualities as as a historical monument and its durability against earthquakes.

6.1.1. Historical Evaluation

Veziraǧa Aqueduct is the most important long-distance water conveyance system of İzmir from Ottoman Period. The aqueduct is the only aqueduct in İzmir whose building date is certainly known. It represents developments in the water supply systems of 17th century İzmir; together with this aqueduct; 10 old fountains were repaired and 73 new fountains were built. In the beginning of the 17th century, the commercial activities increased in İzmir because of the investments of foreigners and the safety of the port. These commercial activities were supported by the Ottoman government, so monuments were donated by the vizier of the period. The two Vezir Khans and Veziraǧa Aqueduct are the most important examples of the investments of the Ottoman State to the city. The fountains provided water to most of the buildings in İzmir city center. The water supply problems of city and people were solved with the building of this aqueduct.

The historical research on other Ottoman aqueducts which date to the same period with the case study shows the general architectural characteristics of the Ottoman aqueducts of this period. These examples are mostly in İstanbul (9/11). In general, the aqueducts have quite similar forms. However, the differences between their heights and lengths, which stem from variation in site conditions, change the number of arches and the form of arch profiles. The aqueducts were generally constructed with depressed (8/11) and sometimes with semi-circular (3/11) arches. Veziraǧa Aqueduct is one of these in İzmir which still stands in its position with the clear information of the original structure. Osmanaǧa and Veziraǧa Aqueducts in İzmir are the two examples of Ottoman period aqueducts in İzmir. Depressed arch profile was the preferred in both of them. The material usage has some differences. In İzmir, rubble stone for the aqueduct structure and brick for the arches, which is not seen in İstanbul examples, were used to construct the aqueducts. The connections of the Veziraǧa Aqueduct shows that the main purpose of the construction was to fulfill the needs of people living in the city center, while most of the other aqueducts were built to carry water to another aqueduct or a lake.

As a special example of Ottoman period aqueducts with its architectural characteristics and construction technique, Veziraǧa Aqueduct has historical significance. The aqueduct is a historical document illuminating the water supply systems in İzmir. The reason of its construction, its construction date, and its location reveals the needs of the period, the importance of water for the community life and the density of the population and extend of commercial life in the city center.

The aqueduct has historical and documentary values because its realization provides information on socio-cultural characteristics of the city in the 17th century. Because of sustaining its authenticity to a great amount, the aqueduct gives information about the construction techniques, material characteristics, and craftsmanship of the 17th century. The information coming from restitution with most reliable sources shows that the aqueduct lost its integrity. However, it still has aesthetic value with its contribution to the picturesque qualities of the landscape comprised of the ancient Kadifekale mount, the valley, the brook and the historical railway.

With all these values and characteristics, the aqueduct must be protected as a historical landmark of İzmir.

6.1.2. Structural Evaluation

Vezirağa Aqueduct is standing in three parts in a first degree earthquake zone. The demolished parts shown in Appendix D2 create weak points for the structure under probable future earthquake loads. In order to comment on resistance of the structure under earthquake load a numerical model generated in Matlab used and to better understand the characteristics of the structure a finite element model and time-history analysis had been generated in commercial software Ansys. The study found in the literature on Vezirağa contains operational modal analysis (OMA), so the model generated can be further improved to get closer to these OMA values and used for further detailed analysis.

For the numerical analysis the most vulnerable piers of two wall portions (A and B) are defined according to their constant values. A code to find out the maximum seismic coefficients, effective natural periods, and the inertia forces affected by the seismic coefficients of the piers is written in Matlab. According to the results of code in Matlab the maximum seismic coefficients and the effective natural periods of the piers are obtained as $\mathrm{c}_{\mathrm{max}_\mathrm{A}} = 0.342396$, $c_{max_B} = 0.20338$, $\mathrm{T}_{\mathrm{s-eff}_\mathrm{A}}: 1.28$ s and $\mathrm{T}_{\mathrm{s-eff}_\mathrm{B}}: 2.17$ s. The maximum inerta forces of the piers under maximum out-of-plane lateral loads and their own weights are $\mathrm{F}_{\mathrm{max}_\mathrm{A}}: 1.4887 * 10^5$ N and $\mathrm{F}_{\mathrm{max}_\mathrm{B}}: 1.3003 * 10^5$ N.

The analyses performed in Ansys are made to find the mode shapes and frequencies of the structure under lateral loads. The structure is modeled in SolidWorks and analyzed by Ansys. The analyses gave six mode shapes and frequencies of the structure. The results for wall portion A are compared with the results of Ercan and Nuhoğlu (2014).

The accelerations of piers are obtained as $a_{0_A} = 0.23\ g$ and $a_{0_B} = 0.14\ g$ which should be checked from the table of peak ground acceleration according to the instrumental intensity (Table 15) to comment on the probable damages during an earthquake. As it is seen in the Table 15 the acceleration of wall portion A is in VII. degree intensity level with very strong ground motion and moderate damage is expected on the structure. For wall portion B, the situation may be safer than wall portion A. The acceleration of wall portion B is in VI. degree intensity level creating strong ground motion and light damage is expected. According to Table 2, there were no earthquakes with very strong or more ground motion since 1900 in İzmir. It is seen that there may not be fully damaging earthquake for the structure. However, the further investigation on structural, material and foundation characteristics should be done for the comment on probable earthquakes.

Table 15. Peak ground acceleration according to the instrumental intensity.
(Source: Peak Ground Acceleration, 2011)

Instrumental Intensity	**Acceleration (g)**	**Velocity (cm/s)**	**Perceived Shaking**	**Potential Damage**
I	< 0.0017	< 0.1	Not felt	None
II-III	0.0017 – 0.014	0.1 – 1.1	Weak	None
IV	0.014 – 0.039	1.1 – 3.4	Light	None
V	0.039 – 0.092	3.4 – 8.1	Moderate	Very light
VI	0.092 – 0.18	8.1 – 16	Strong	Light
VII	0.18 – 0.34	16 – 31	Very Storng	Moderate
VIII	0.34 – 0.65	31 – 60	Severe	Moderate to heavy
IX	0.65– 1.24	60 – 116	Violent	Heavy
X+	> 1.24	> 116	Extreme	Very heavy

The maximum displacements of the aqueduct during El Centro earthquake has been found by time-history analysis. The biggest movements of the aqueduct have been seen at the south end of wall portion A.

According to the results from analyses, the structure might suffer from major earthquakes. In order to better understand and investigate the behavior of the structure, further analysis should be performed. In elastic dynamic analysis using either modal superposition or time history analysis should be performed, and locations that are expected to be stressed over or around the capacity of the masonry should be determined. And intervention decision should be made depending on whether or not strengthening of the walls would be required. The Ansys model generated in this study after refinement can serve well to this purpose.

6.2. Conclusion

This study identifies the historical, architectural and structural characteristics of Vezirağa Aqueduct as a historical monument in İzmir. It should be considered within the scope of landscape planning and conservation as a rare historical monument documenting the status of İzmir city in the 17th century and representing the value of water and water structures in the past.

The structural resistances against the lateral loads are defined to understand the risks for the structure. The results show that the aqueduct may answer the acceptable lateral loads and earthquakes which are possible to occur in İzmir. It can continue to its life span under current circumstances. However, detailed investigations on foundation, effects of traffic, and effects of site characteristics should be practiced to underline the possible future structural failures.

The aqueduct has authenticity, historical, documentary and technical values, but it has lost its integrity. Vista points and observation terraces may be proposed to present the aqueduct and emphasize it as a landmark in the city silhouette. Cleaning of the housing area at its south may be considered.

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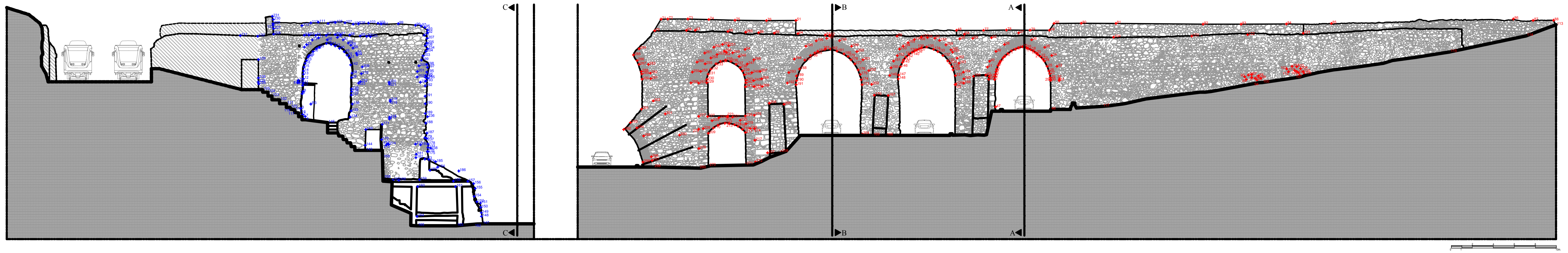
APPENDIX A

METHODOLOGY

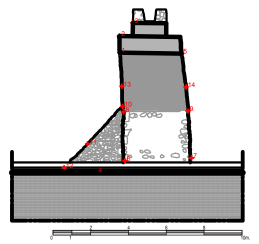
A THESIS Submitted to the Graduate School
of Engineering and Sciences of
İZMİR INSTITUTE OF TECHNOLOGY
for the Degree of
MASTER OF SCIENCE
of ARCHITECTURAL RESTORATION

IDENTIFICATION OF
VEZİRAĞA AQUEDUCT IN İZMİR
AS A HISTORICAL MONUMENT

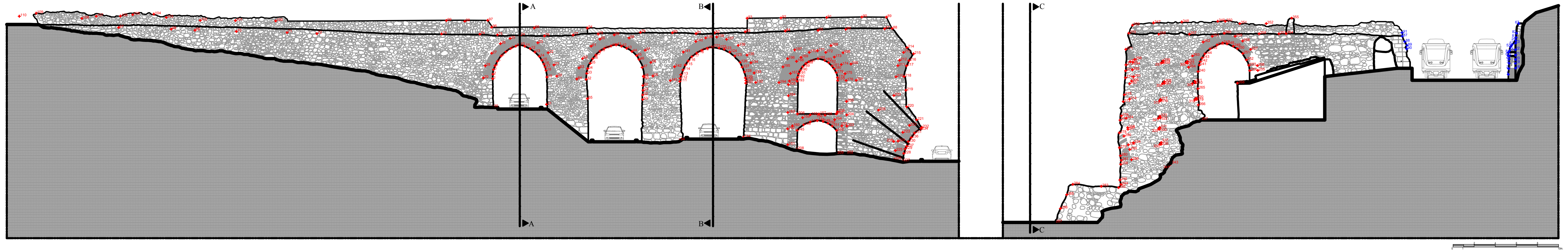
İzmir, 2016



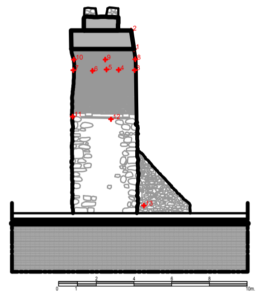
THEODOLITE POINTS
EAST ELEVATION



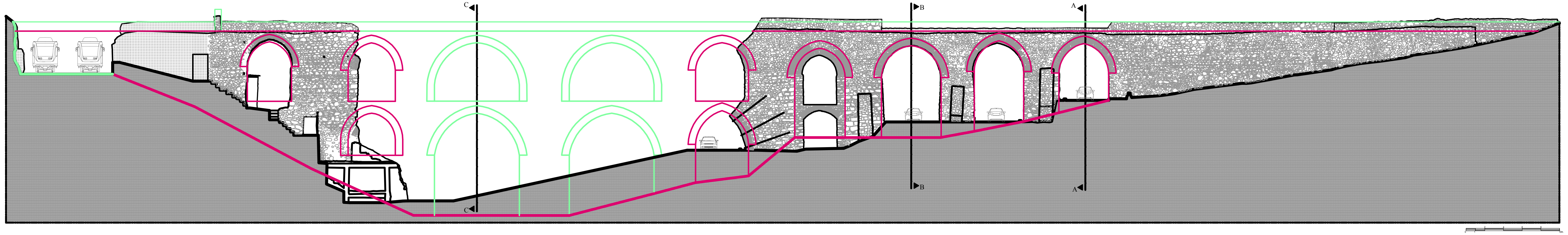
THEODOLITE POINTS
SECTION AA



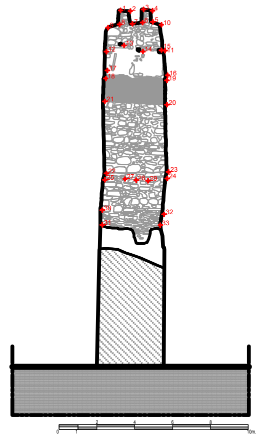
THEODOLITE POINTS
WEST ELEVATION



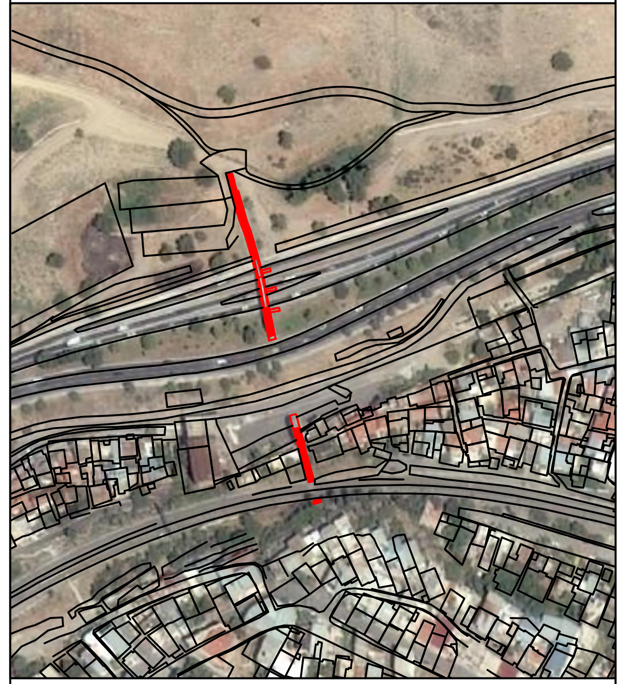
THEODOLITE POINTS
SECTION BB



METHOD OF RESTITUTION
EAST ELEVATION



THEODOLITE POINTS
SECTION CC



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Co-Supervisor:
Assoc. Prof Dr. Engin AKTAŞ

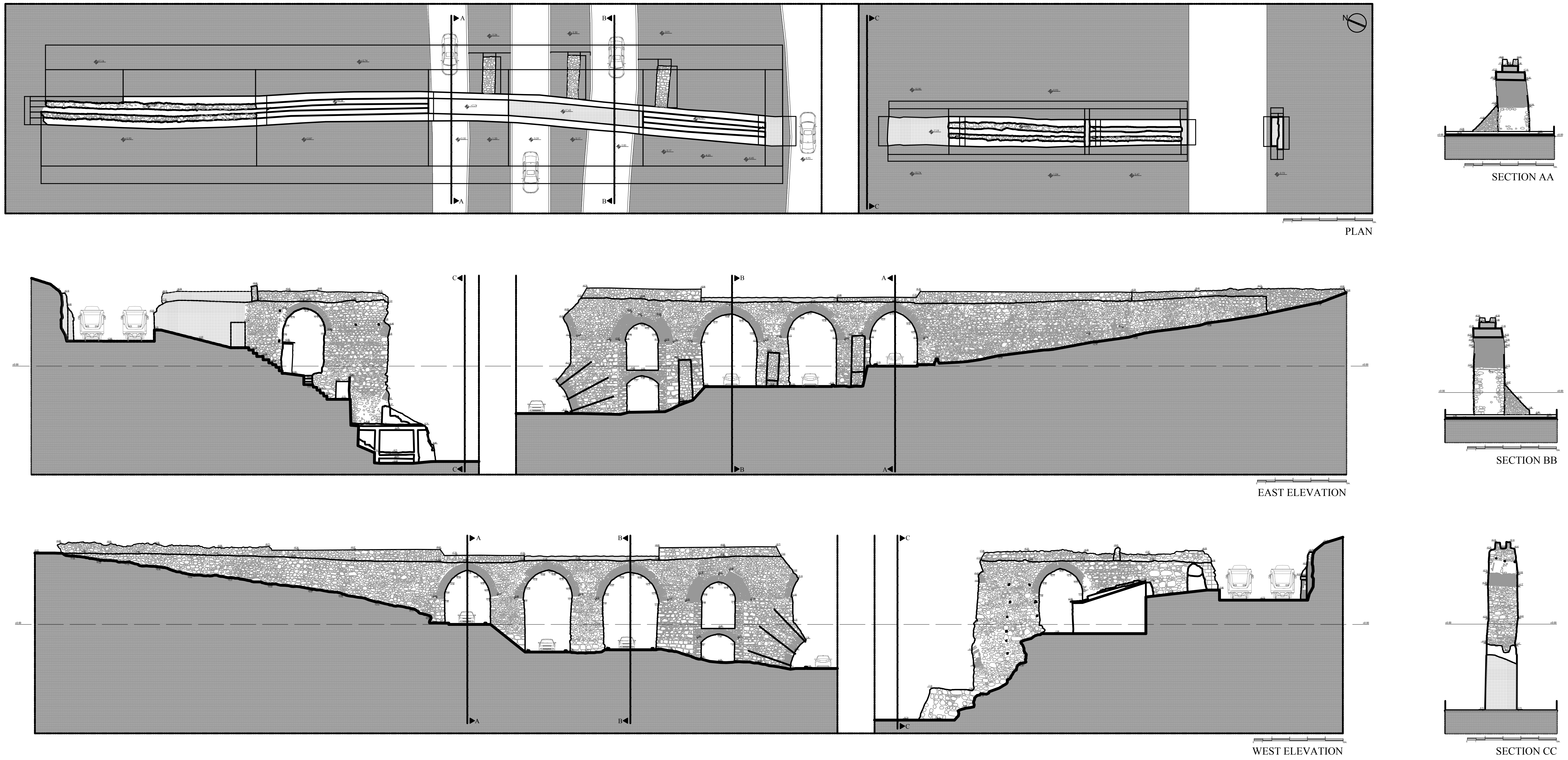
- [x] METHODOLOGY
- [ ] ANALYSIS
- [ ] MEASURED DRAWING
- [ ] RESTITUTION

THEODOLITE POINTS
METHOD OF RESTITUTION

Appendix A: Methodology

APPENDIX B

MEASURED DRAWINGS



A THESIS Submitted to the Graduate School
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for the Degree of
MASTER OF SCIENCE
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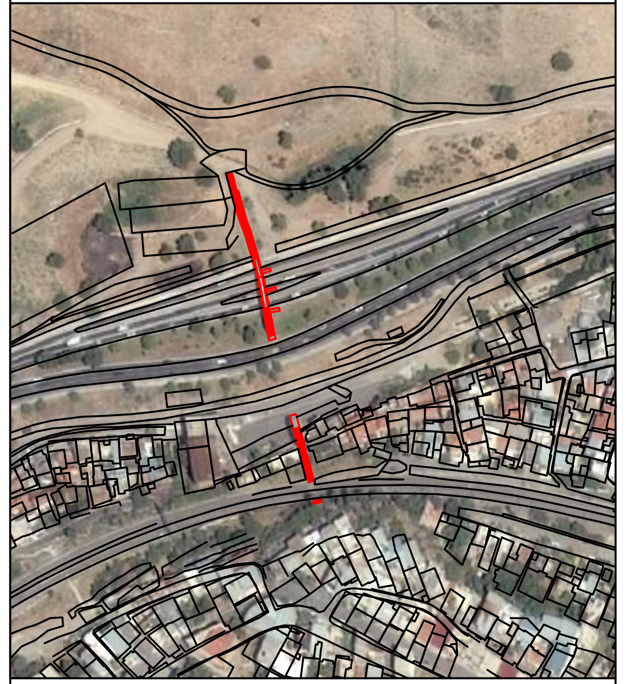
IDENTIFICATION OF
VEZİRAĞA AQUEDUCT IN İZMİR
AS A HISTORICAL MONUMENT

İzmir, 2016



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- [ ] METHODOLOGY
- [x] MEASURED DRAWING
- [ ] ANALYSIS
- [ ] RESTITUTION

MEASURED DRAWINGS
OF VEZİRAĞA AQUEDUCT

Appendix B: Measured Drawings

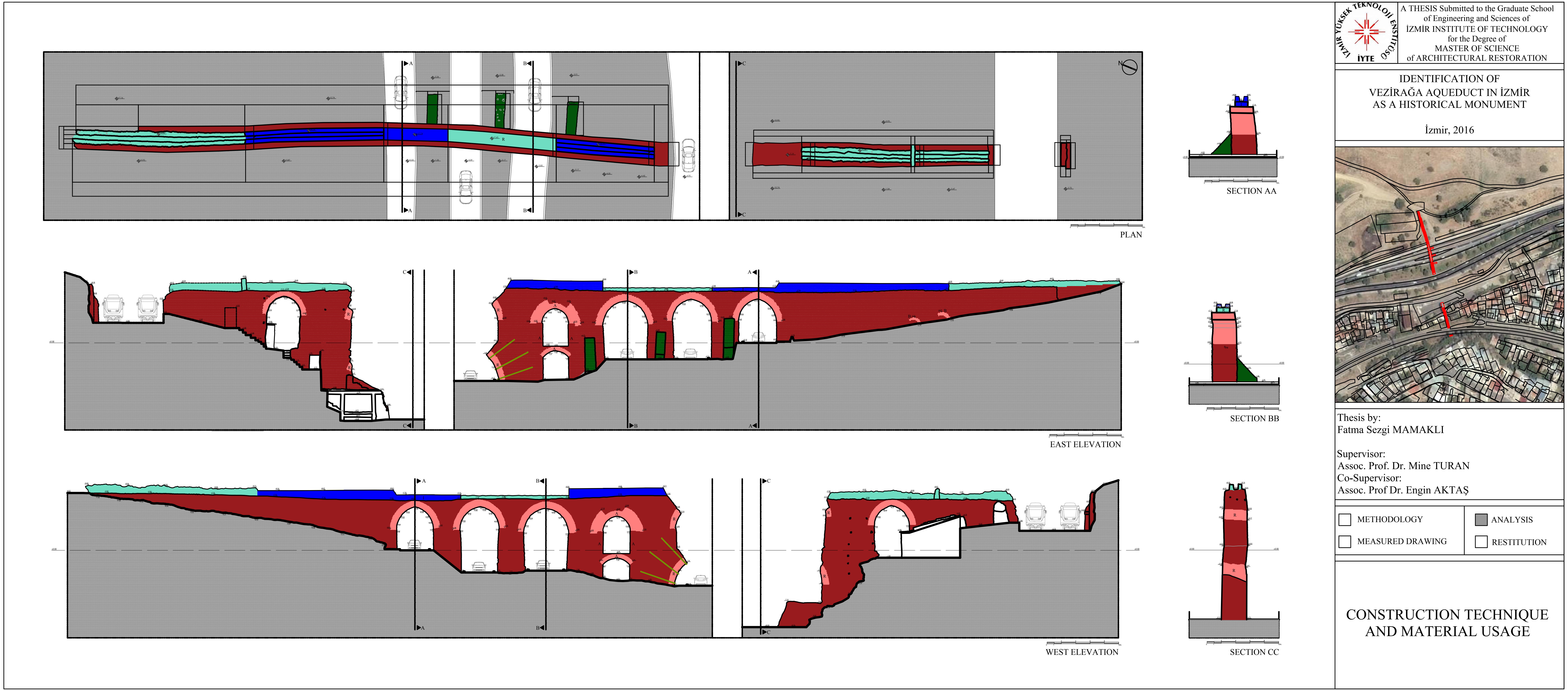
APPENDIX C

CONSTRUCTION TECHNIQUE AND MATERIAL USAGE

CONSTRUCTION TECHNIQUE AND MATERIAL USAGE

STRUCTURAL ELEMENTS	STONE MASONRY WALL SYSTEM Stone masonry wall composed of three independent portions (length of A: 81.30 m, length of B: 14.50 m, length of C: 1.00 m) in north-south direction on the four-lined road, composed of rubble stones and mortar, corners reinforced with cutstone, some antique stones reused in the composition, exposed without plastering and paint	A - Additional
	BRICK MASONRY ARCH SYSTEM Three brick masonry arches on the A of stone masonry wall in east-west direction on the road, composed of bricks and mortar, exposed without plastering and paint. Two brick masonry arches on the A of stone masonry wall in east-west direction on refuge one above the other, composed of brick and mortar, exposed without plastering and paint. One brick masonry arch on the B of stone masonry wall in east-west direction between the housing units, composed of bricks and mortar, exposed without plastering and paint	A - Additional R - Remain B - Blind
	BUTTRESSES Two stone masonry buttresses supporting wall portion A between its arches at the east facade, triangle shaped, back to back with stone masonry wall, composed of rubble stones and mortar, exposed without plastering and paint	
	WOODEN HORIZONTAL LINTELS Wooden beams (Ø:8 cm) in east-west direction on the collapsed part of B of the stone masonry wall	
	IRON REINFORCEMENT Six iron bars (R:2 cm) in north-south direction on the collapsed part of A of the stone masonry wall	
ARCHITECTURAL ELEMENTS	STONE DUCT Stone masonry duct (L: 17.51 m) with U profile above the A of the stone masonry wall in north west direction, composed of rubble stones, corner stones and mortar, exposed without plastering and paint. Stone masonry duct (L: 25.80 m) with U profile above the B of the stone masonry wall in north west direction, composed of rubble stones and mortar, exposed without plastering and paint The remain of stone duct (L: 15.11 m) above wall portion A, composed of rubble stones and mortar, exposed without plastering and paint The remain of stone duct (L: 1.00 m) above wall portion C, composed of rubble stones and mortar, exposed without plastering and paint	R - Remain
	CONCRETE COVERED STONE DUCT Concrete covered stone duct in two parts (L_1: 18.90 m, L_2: 13.20 m) with U profile above wall portion A in north west direction, constructed by stone and covered with concrete from the inside of U profile Incomplete concrete covered stone duct (L: 9.05 m) piece at the south of the concrete covered stone duct above the wall portion A	I - Incomplete

Appendix C1: Construction Technique and Material Usage



Appendix C2: Construction Technique and Material Usage, Analysis

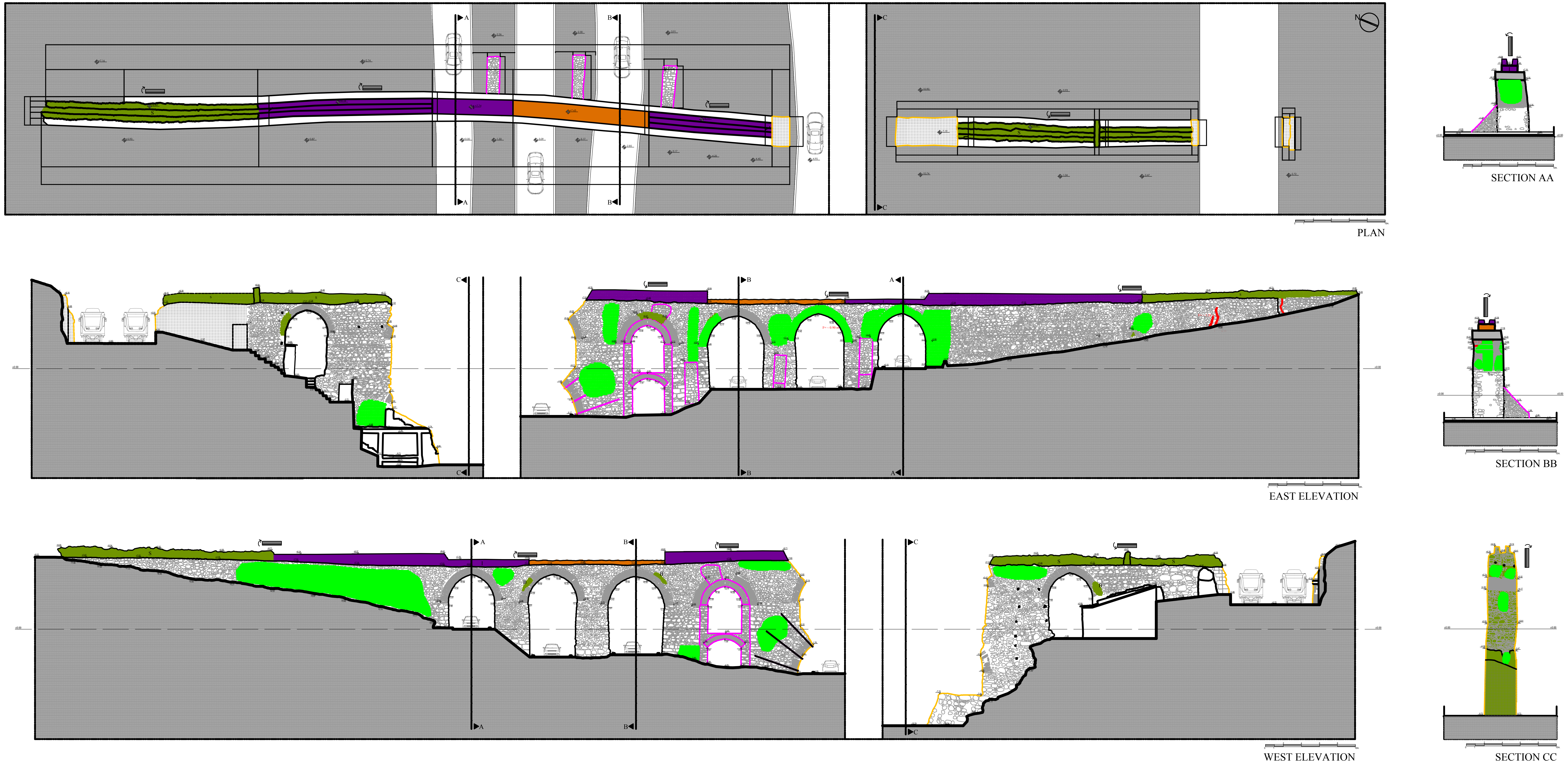
APPENDIX D

STRUCTURAL FAILURES, MATERIAL DETERIORATIONS AND ALTERATIONS

STRUCTURAL FAILURES, MATERIAL DETERIORATIONS AND ALTERATIONS

STRUCTURAL FAILURES		DEMOLISHMENT Two demolished parts of the stone masonry wall on the main road and on the railway, jeopardizes the stability of the wall and causes loss of structural integrity	
STRUCTURAL FAILURES		OUT OF PLUMBNESS Wall portion A leaning to east direction Wall portion B leaning to west direction	
STRUCTURAL FAILURES		FRACTURE Horizontal fractures along arch-wall connections in east-west direction Vertical fractures on the walls continuing from top to bottom Diagonal fractures within the arches	F - Fracture Length
MATERIAL DETERIORATIONS		LOSS OF MATERIALS Loss of brick materials on the arches Loss of stone materials on duct	
MATERIAL DETERIORATIONS		DISCOLORATION Discoloration on iron bars, wooden horizontal lintels, bricks and plasters	
ALTERATIONS	INTERVENTIONS	STRUCTURAL ADDITIONS Addition of an arch system of wall portion A with two new arches and stone-brick wall Stone masonry buttresses to the east facade of wall portion A Iron bars to the demolished part of wall portion A	
ALTERATIONS	INTERVENTIONS	RECONSTRUCTIONS Reconstruction of the duct of wall portion A with concrete Incomplete reconstruction of the duct of wall portion A with concrete	I - Incomplete
ALTERATIONS	LOSSES	ARCHITECTURAL ELEMENT LOSS Partial loss of stone duct on wall portion A	

Appendix D1: Structural Failures, Material Deteriorations and Alterations



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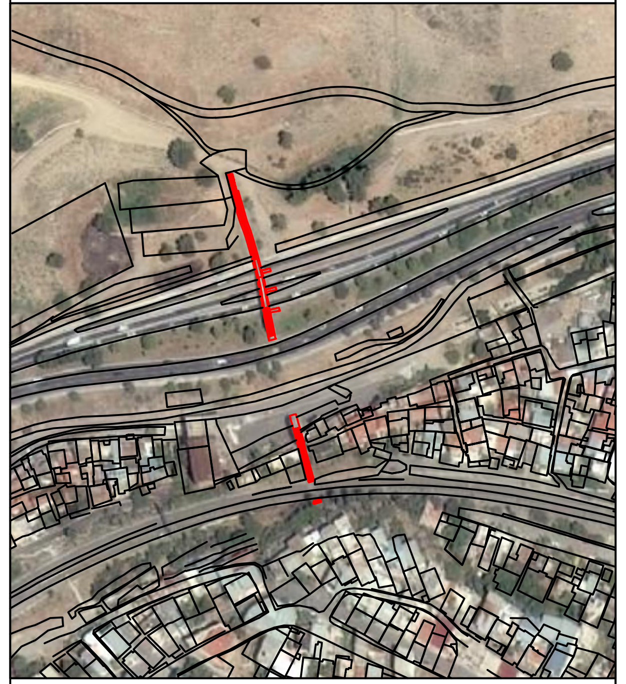

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☐ METHODOLOGY ■ ANALYSIS
☐ MEASURED DRAWING ☐ RESTITUTION

STRUCTURAL FAILURES,
MATERIAL DETERIORATIONS
AND ALTERATIONS

Appendix D2: Structural Failures, Material Deteriorations and Alterations, Analysis

APPENDIX E

NUMERICAL AND MATHEMATICAL ANALYSIS

```
function [FARK BB ygcmax F K T]=veziragafunction(c,beta)
Data_Veziraga;
ec(1)=0;
yc(1)=0;
for j=0:n-1
    if ec(j+1)>=0
        if ec(j+1)<=1/6
          lambda(j+1)=12*(ec(j+1));
        else
            lambda(j+1)=2/(9*(1/2-ec(j+1))^2);
        end
    end
    phic(j+1)=A*ksi*(j+1)*lambda(j+1);
    CC=0;
    for i=1:j+1
        CC=CC+ksi^2*phic(i);
    end
    yc(j+2)=yc(j+1)+ksi*beta+0.5*ksi^2*phic(j+1)*D-CC;
    ygc(j+1)=yc(j+1)+0.5*ksi*beta+3/8*ksi^2*phic(j+1)-
0.5*CC;
    DD=0;
    EE=0;
    for i=1:j+1
        DD=DD+ygc(i);
        EE=EE+(n-i+1/2)*((j+1)-i+1/2);
    end
    ec(j+2)=yc(j+2)-1/(j+2)*DD+c*ksi*1/((j+2)*(n-1/2))*EE;
end
BB=0;
```

```
F=0;
for i=1:n
    BB=BB+ksi*phic(i);
    F=F+c*((n-i+0.5)/(n-0.5))*W/n;
end
FARK=beta-BB;
ygcmax=D*ygc(length(ygc));
end
```

Appendix E1: The function written in Matlab for analysis model

```
n=19;
gama=21 ; % 'kN/m3'
gama=gama*1e3; % 'N/m3'
E=871; %'MPa'
E=E*1e6; %Pa N/m2
H=12.60; %'m'
D=3.20; % 'm'
B=3.30; %'m'
B=1.00; %'m'
g=9.81; %'m/s2'
A=gama*D/E;
SR=H/D;
ksi=SR/n;
W=H*D*gama;
M=W/g;
Me=(3/4)*M;
a=0.345719/(1.95*0.75); %*g
F1=0.345719*W/1.95;
Fs=Me*a*g;
```

Appendix E2: The constant data in Matlab for wall portion A

```
n=29;
gama=21 ; % 'kN/m3'
gama=gama*1e3; % 'N/m3'
E=871; %'MPa'
E=E*1e6; %Pa N/m2
H=18.70; %'m'
D=3.20; % 'm'
B=3.30; %'m'
B=1.00; %'m'
g=9.81; %'m/s2'
A=gama*D/E;
SR=H/D;
ksi=SR/n;
W=H*D*gama;
M=W/g;
Me=(3/4)*M;
a=0.345719/(1.95*0.75); %*g
F1=0.345719*W/1.95;
Fs=Me*a*g;
```

Appendix E3: The constant data in Matlab for wall portion B

```
c=[0.05:0.001:0.342 0.342001:0.000001:0.342396];
AA=[0 0];
beta=0.001;
for i=1:length(c)
for j=1:200
    [FARK BB ygcmax F]=veziragafunction(c(i),beta);
    if abs(FARK)<1e-5
        AA(i+1,1)=c(i);
        AA(i+1,2)=ygcmax;
        AA(i+1,3)=F;
        AA(i+1,4)=BB;
        AA(i+1,5)=j;
```

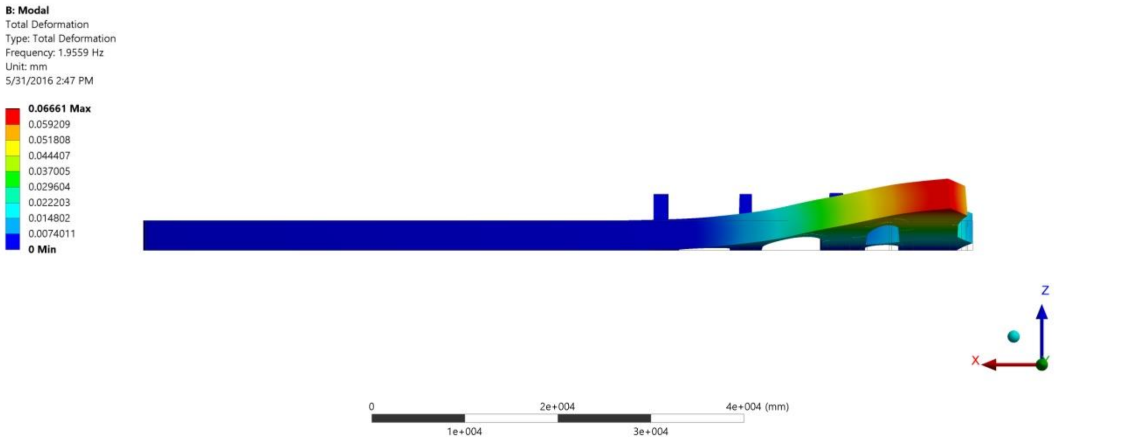
```
        beta=BB;
        break
    else if FARK<0
            beta=beta*1.10;
        else
            beta=beta*0.90;
        end
    end
end
end
for i=1:length(AA(:,2))
    if (AA(i,2)<AA(end,2)/2)
    else
        check=i
        break
    end
end
figure
plot(AA(:,2)*100,AA(:,1))
xlabel('Lateral displacement at the top, \delta (cm.)')
ylabel('Seismic Coefficient, c')
xlim([0 25])
grid on
figure
plot(AA(:,2)*100,AA(:,3)*1e-3)
xlabel('Lateral displacement at the top, \delta (cm.)')
ylabel('Resultant Out-of-Plane Force, (kN)')
xlim([0 25])
grid on
Kseff=AA(check,3)/AA(check,2);
Tseff=2*pi/(sqrt(Kseff/Me));
```

Appendix E4: The program written for the results in Matlab for wall portion A

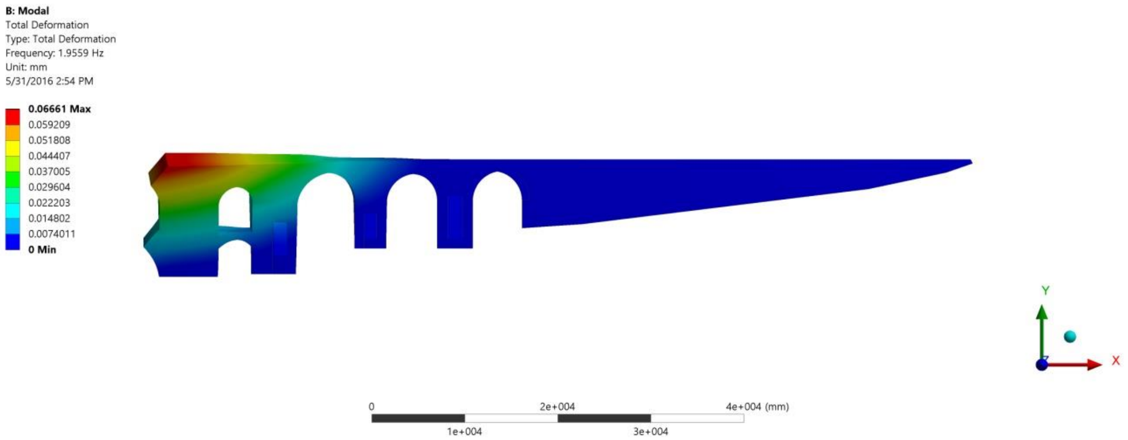
```
c=[0.05:0.001:0.20 0.200001:0.000001:0.20338];
AA=[0 0];
beta=0.001;
for i=1:length(c)
for j=1:300
    [FARK BB ygcmax F]=veziragafunction(c(i),beta);
    if abs(FARK)<1e-5
        AA(i+1,1)=c(i);
        AA(i+1,2)=ygcmax;
        AA(i+1,3)=F;
        AA(i+1,4)=BB;
        AA(i+1,5)=j;
        beta=BB;
        break
    else if FARK<0
            beta=beta*1.10;
        else
            beta=beta*0.90;
        end
    end
end
end
for i=1:length(AA(:,2))
    if (AA(i,2)<AA(end,2)/2)
    else
        check=i
        break
    end
end
figure
plot(AA(:,2)*100,AA(:,1))
xlabel('Lateral displacement at the top, \delta (cm.)')
ylabel('Seismic Coefficient, c')
xlim([0 35])
```

```
grid on
figure
plot(AA(:,2)*100,AA(:,3)*1e-3)
xlabel('Lateral displacement at the top, \delta (cm.)')
ylabel('Resultant Out-of-Plane Force, (kN)')
xlim([0 35])
grid on
Kseff=AA(check,3)/AA(check,2);
Tseff=2*pi/(sqrt(Kseff/Me));
```

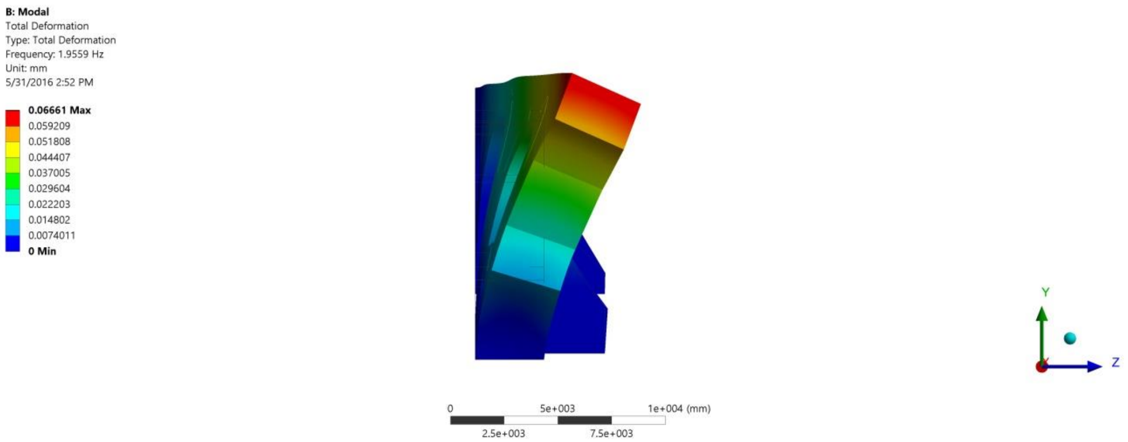
Appendix E5: The program written for the results in Matlab for wall portion B



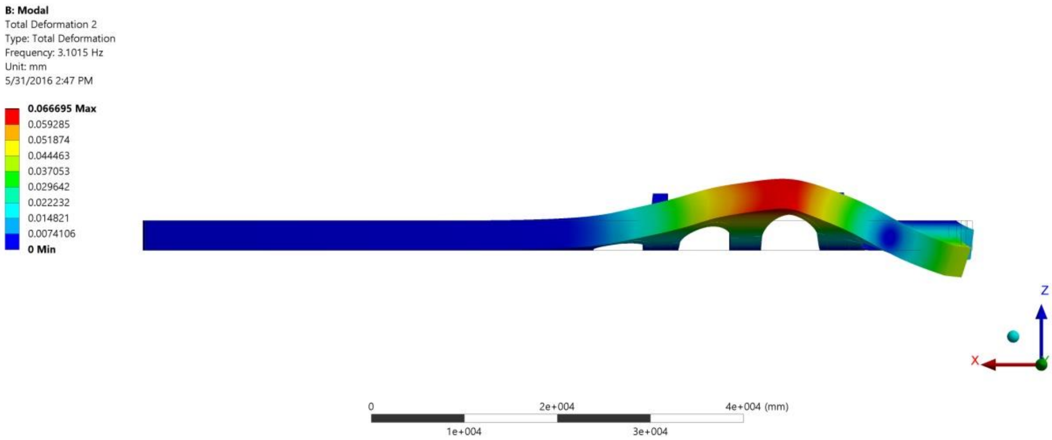
Appendix E6. First mode shape of wall portion A on plan.



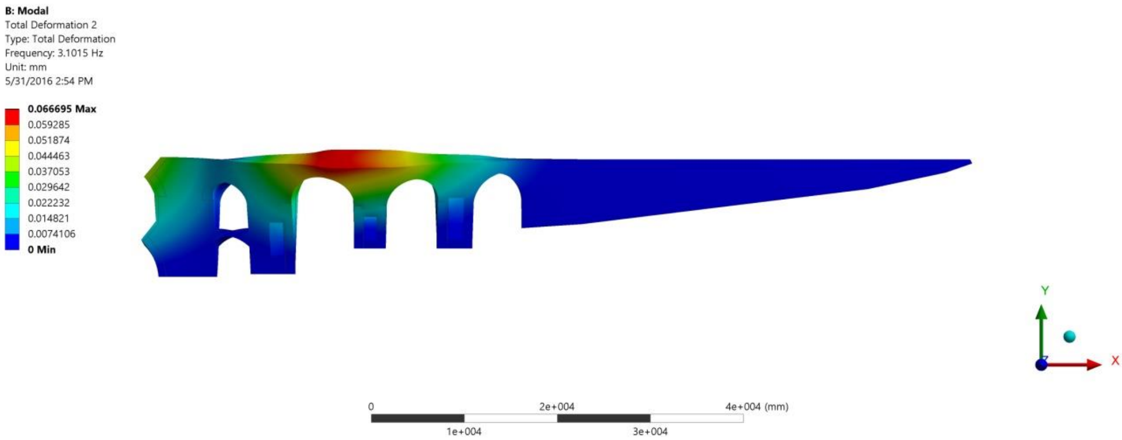
Appendix E7. First mode shape of wall portion A on east elevation.



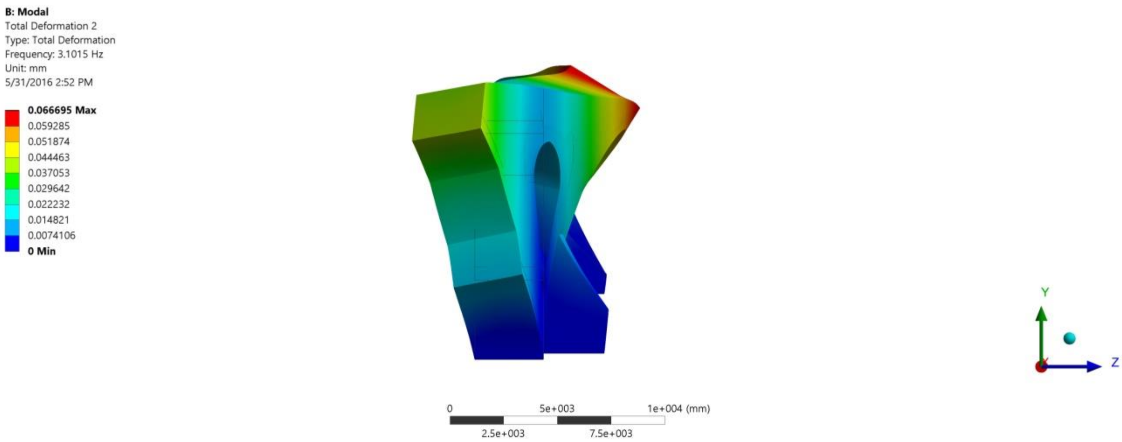
Appendix E8. First mode shape of wall portion A at south end.



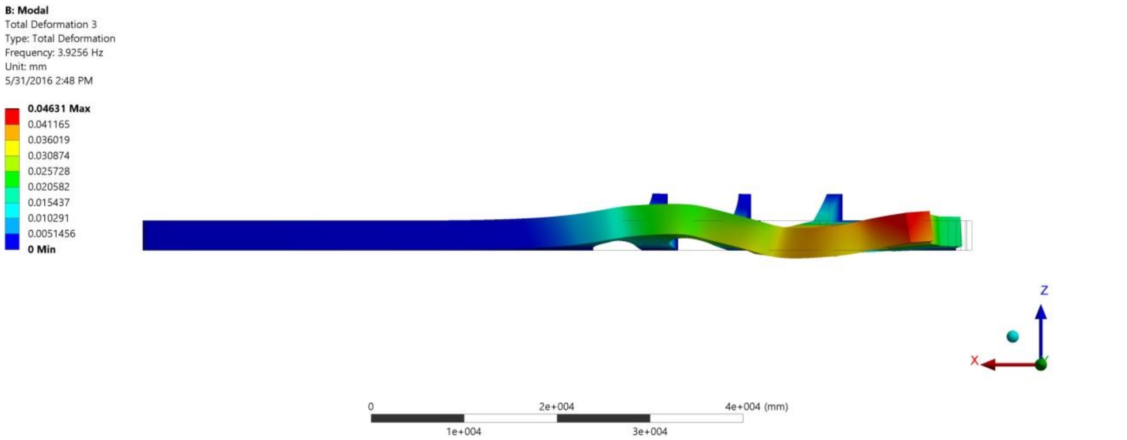
Appendix E9. Second mode shape of wall portion A on plan.



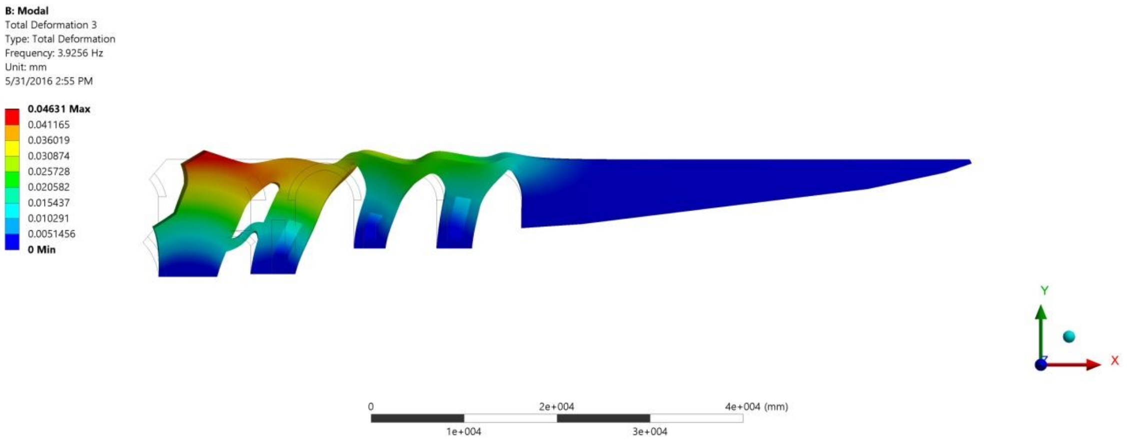
Appendix E10. Second mode shape of wall portion A on east elevation.



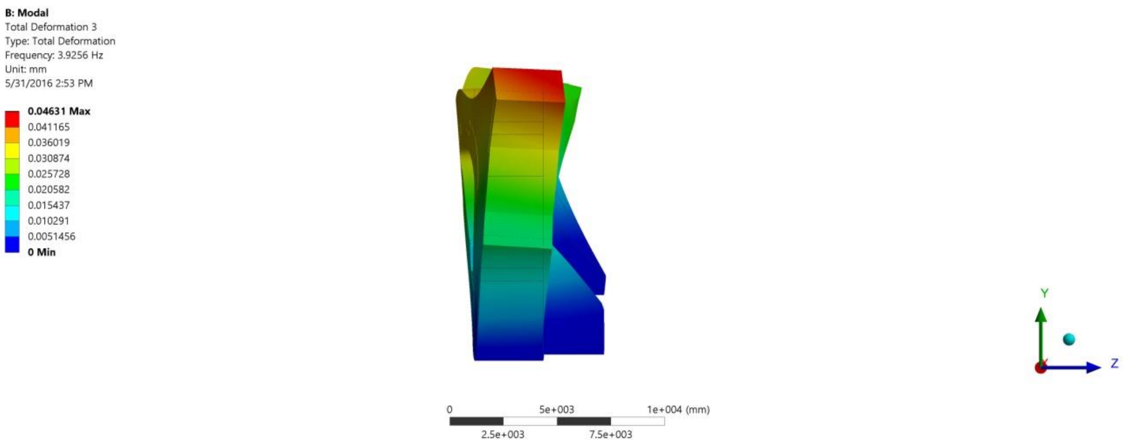
Appendix E11. Second mode shape of wall portion A at south end.



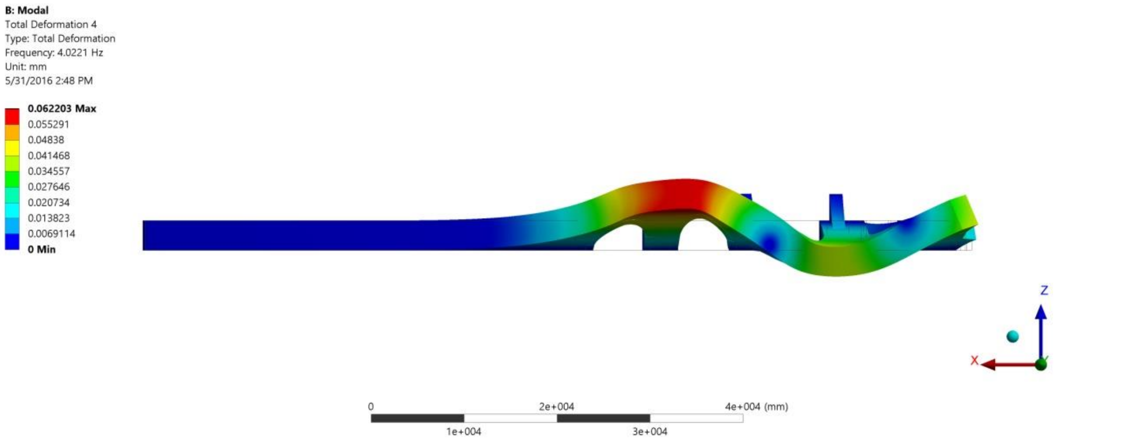
Appendix E12. Third mode shape of wall portion A on plan.



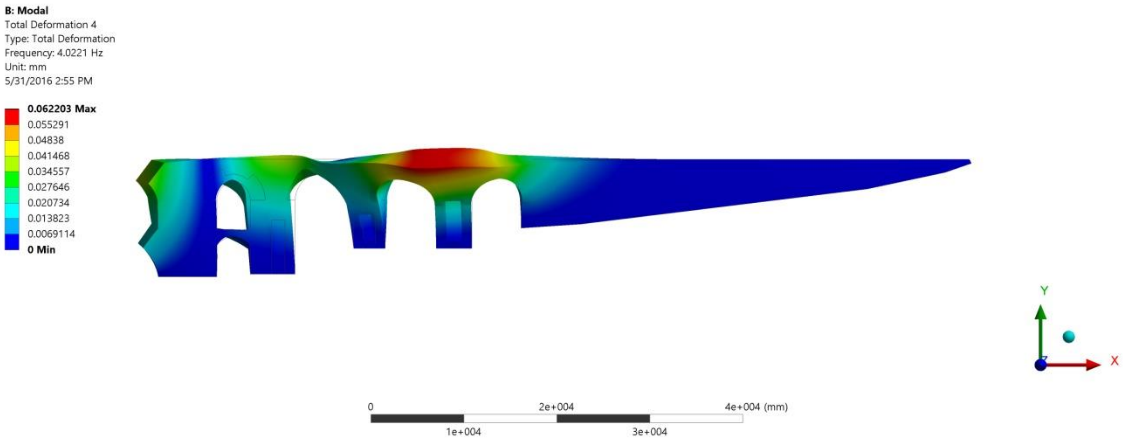
Appendix E13. Third mode shape of wall portion A on east elevation.



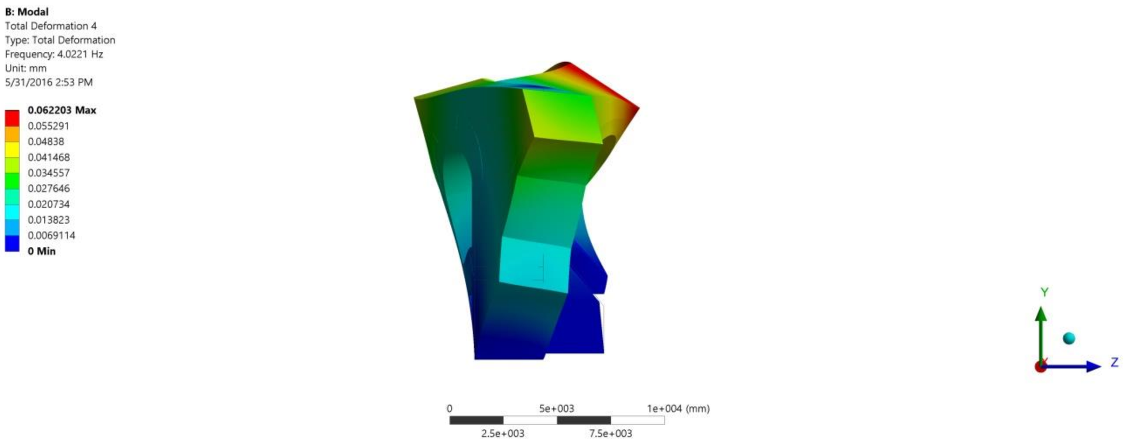
Appendix E14. Third mode shape of wall portion A at south end.



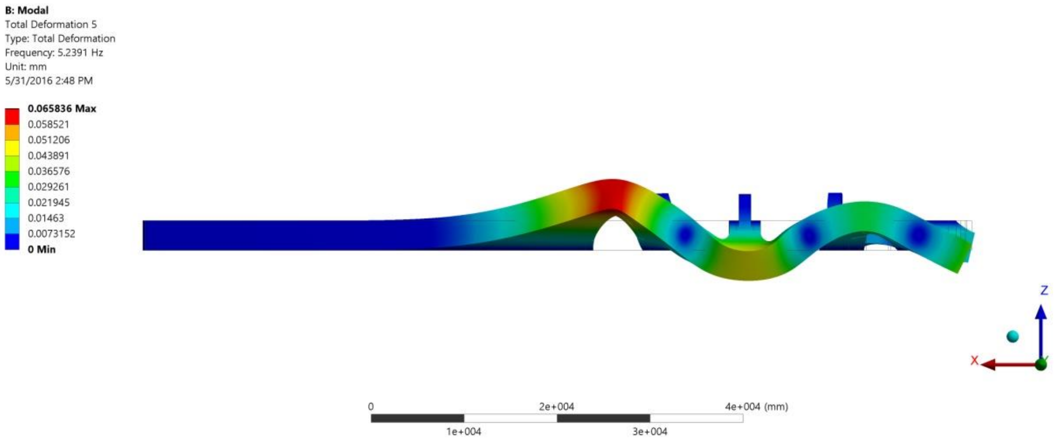
Appendix E15. Fourth mode shape of wall portion A on plan.



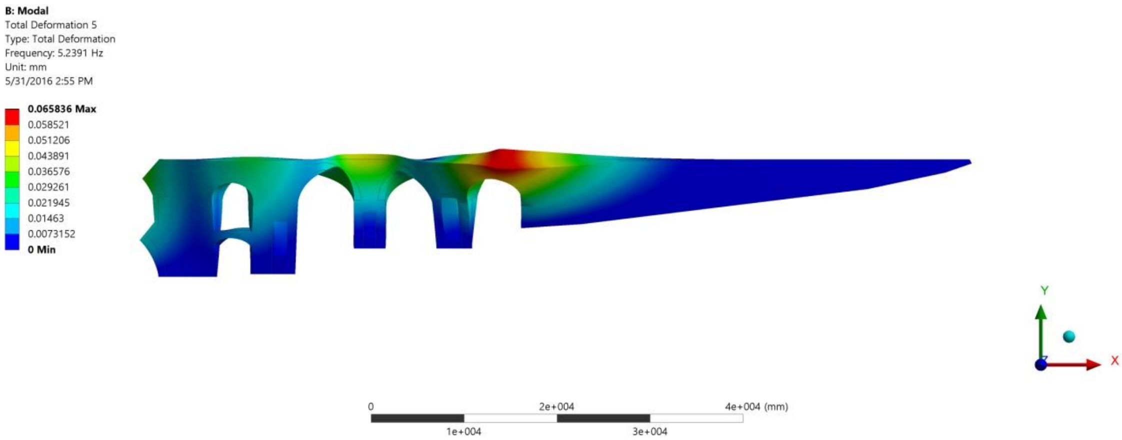
Appendix E16. Fourth mode shape of wall portion A on east elevation.



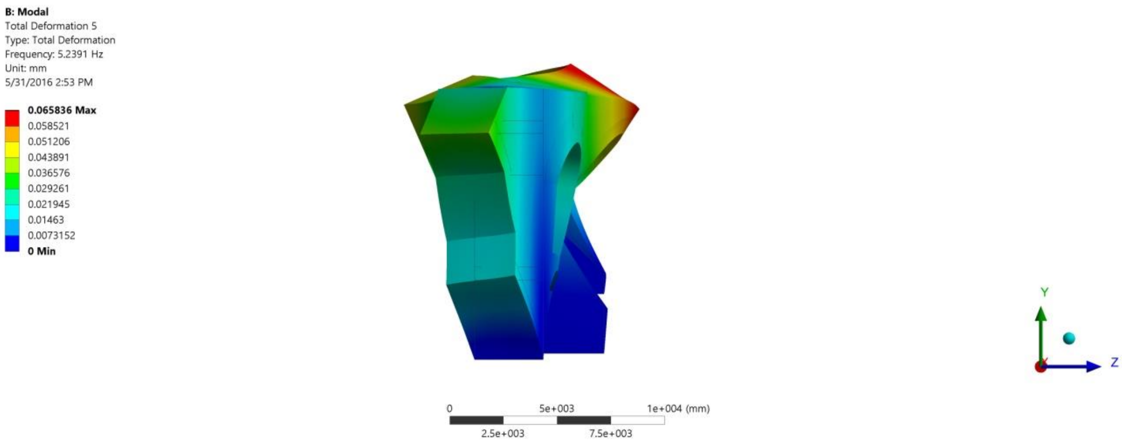
Appendix E17. Fourth mode shape of wall portion A at south end.



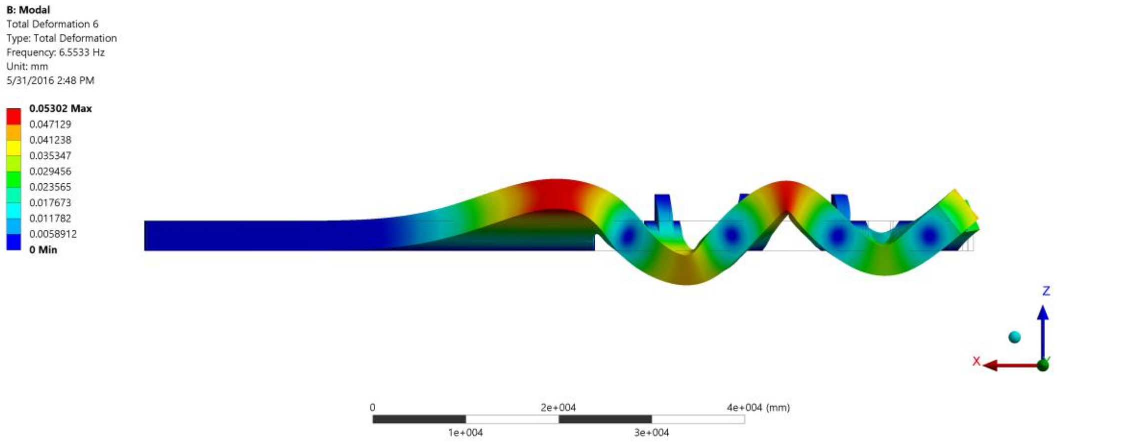
Appendix E18. Fifth mode shape of wall portion A on plan.



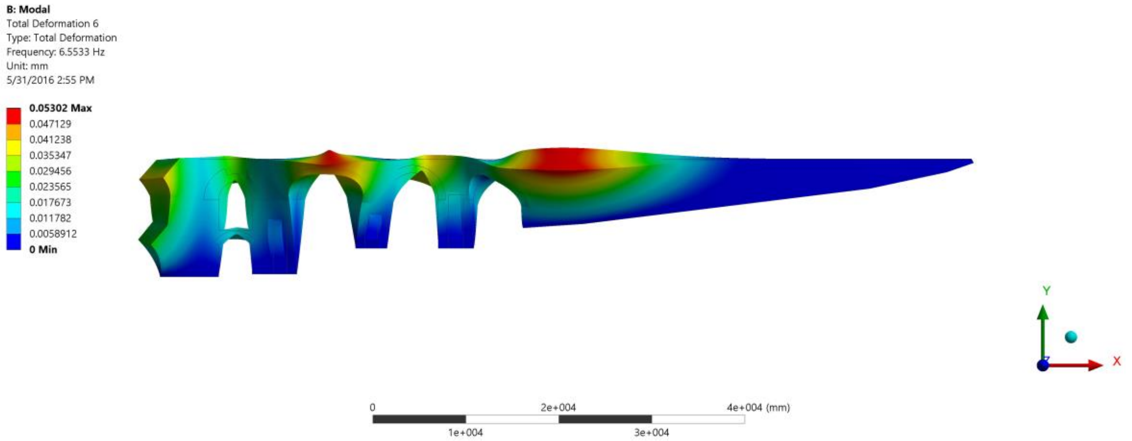
Appendix E19. Fifth mode shape of wall portion A on east elevation.



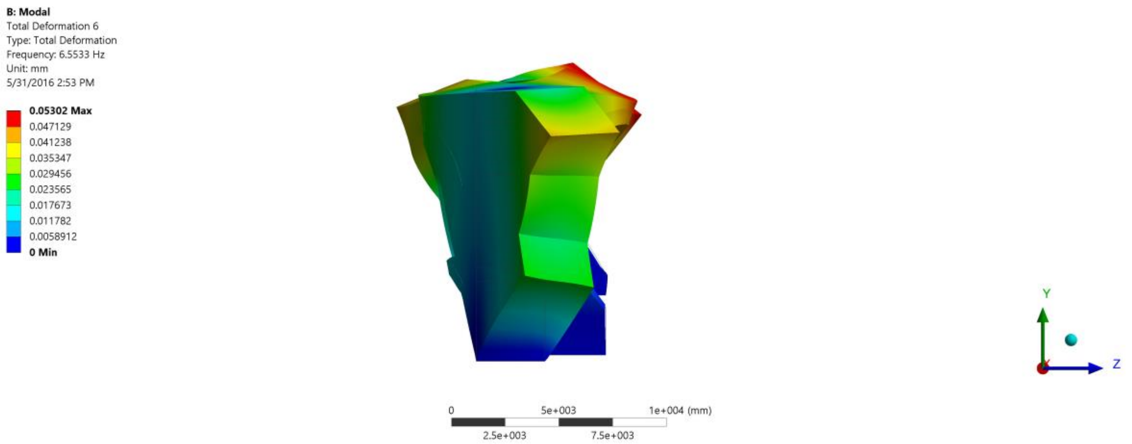
Appendix E20. Fifth mode shape of wall portion A at south end.



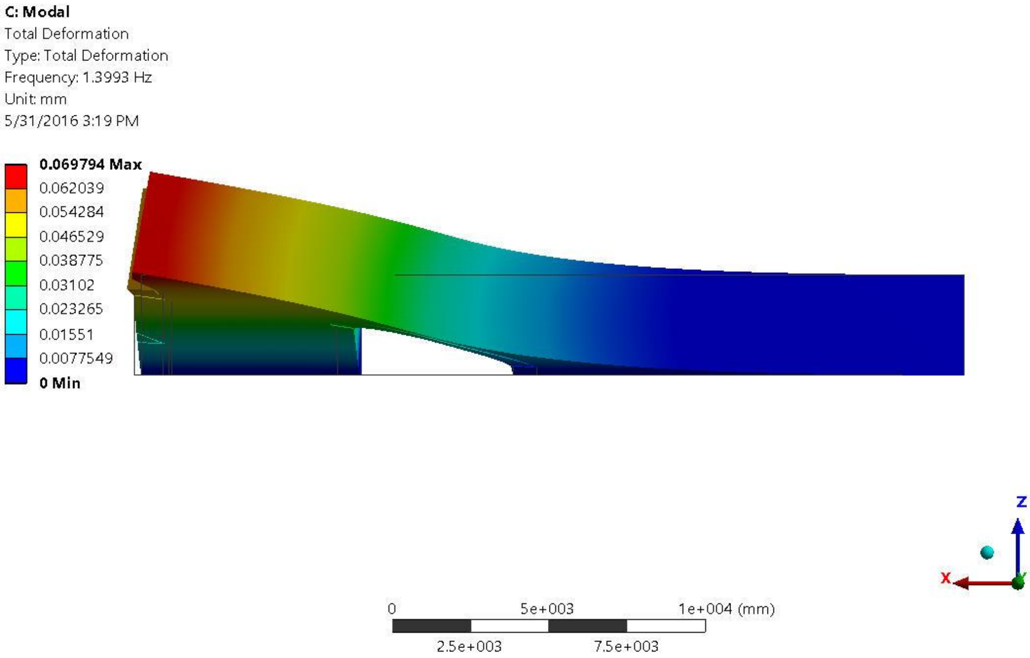
Appendix E21. Sixth mode shape of wall portion A on plan.



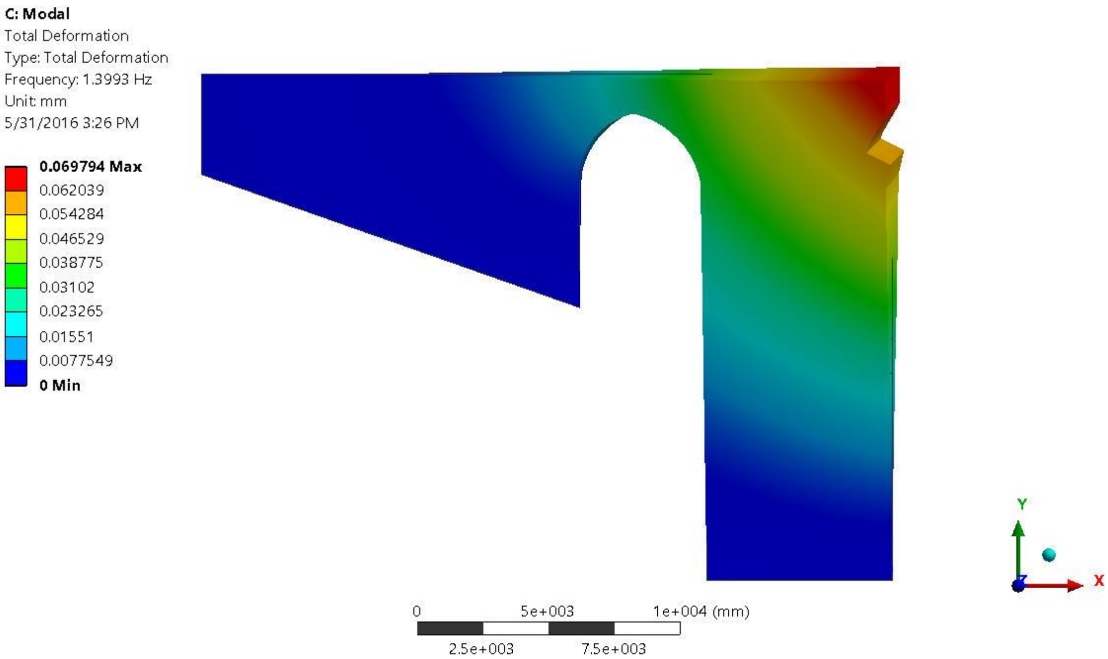
Appendix E22. Sixth mode shape of wall portion A on east elevation.



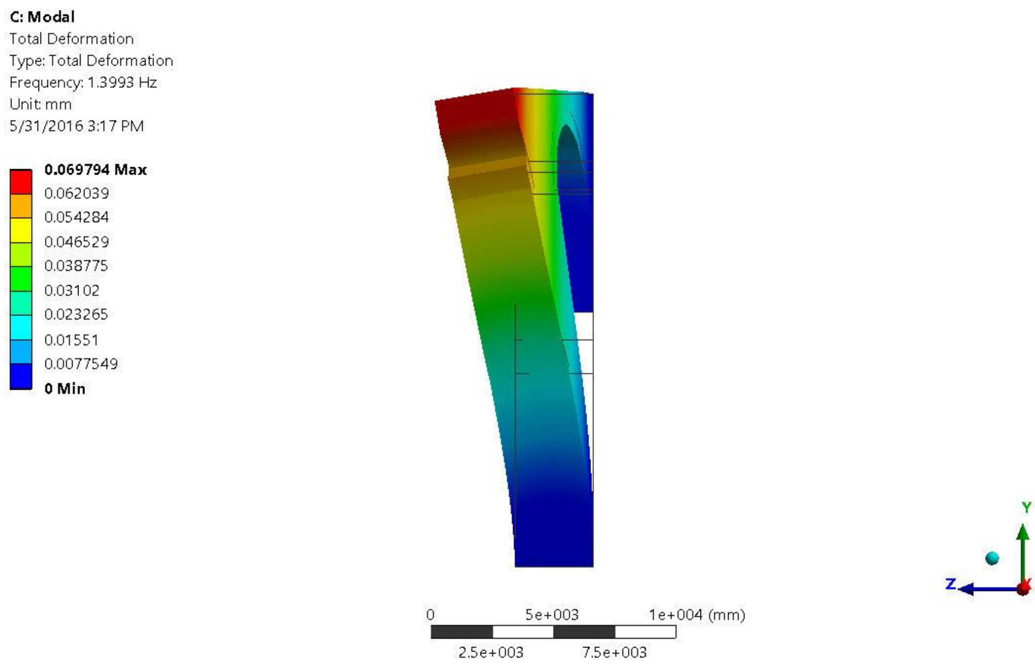
Appendix E23. Sixth mode shape of wall portion A at south end.



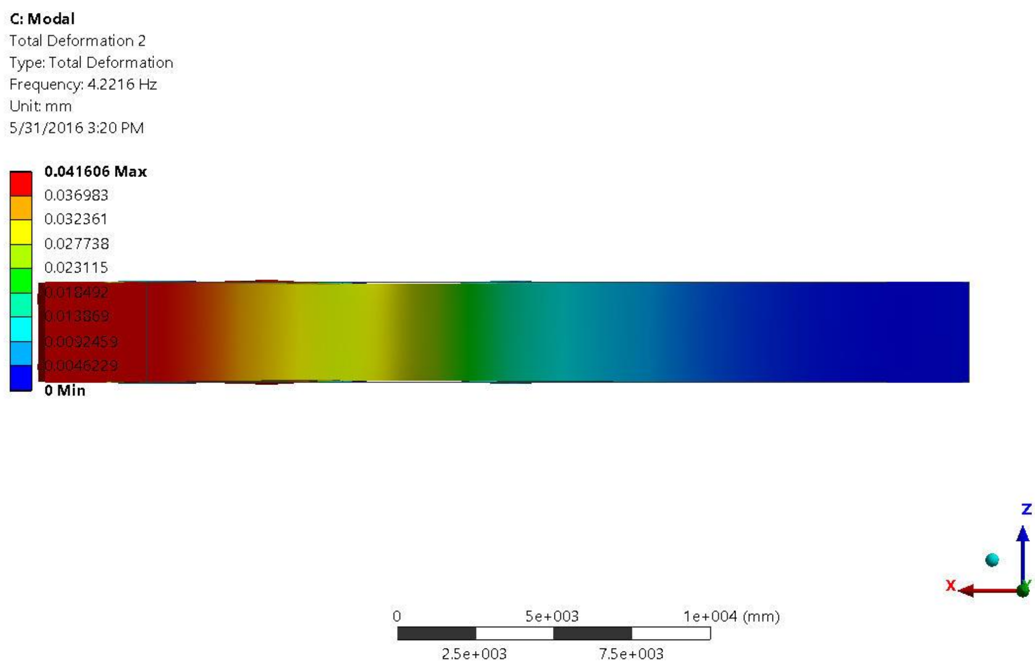
Appendix E24. First mode shape of wall portion B on plan.



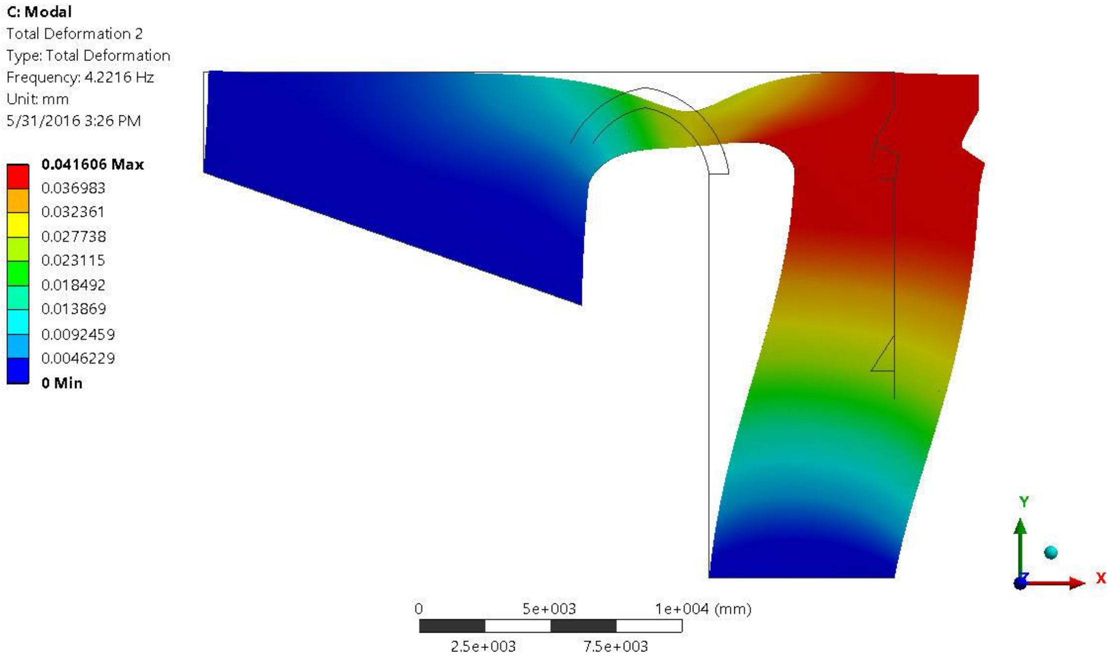
Appendix E25. First mode shape of wall portion B on east elevation.



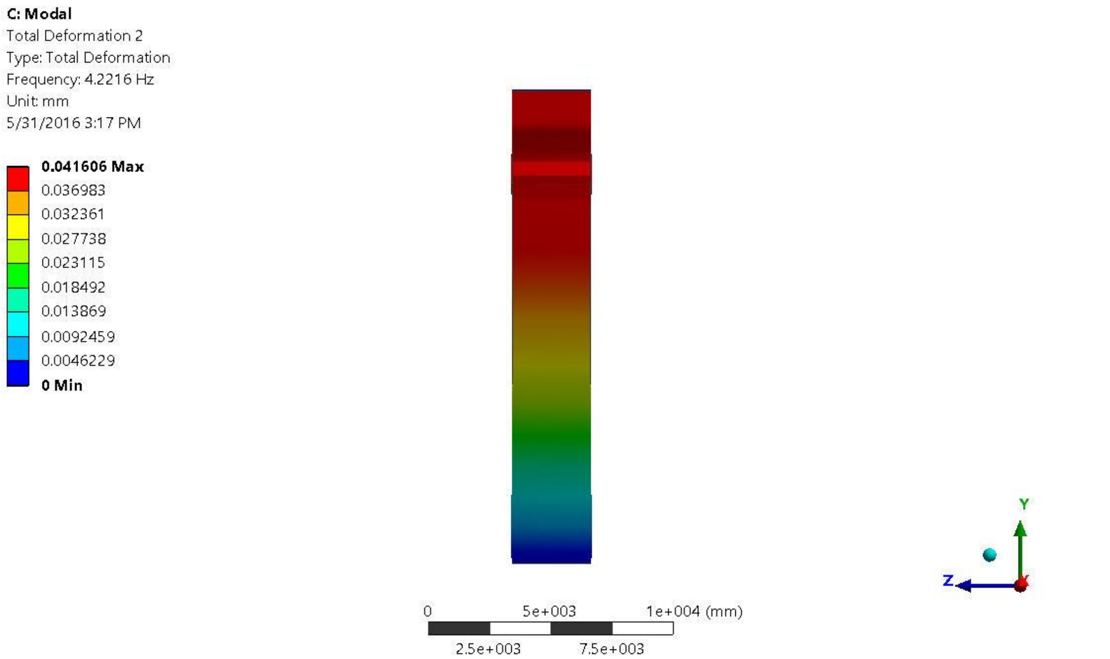
Appendix E26. First mode shape of wall portion B at north end.



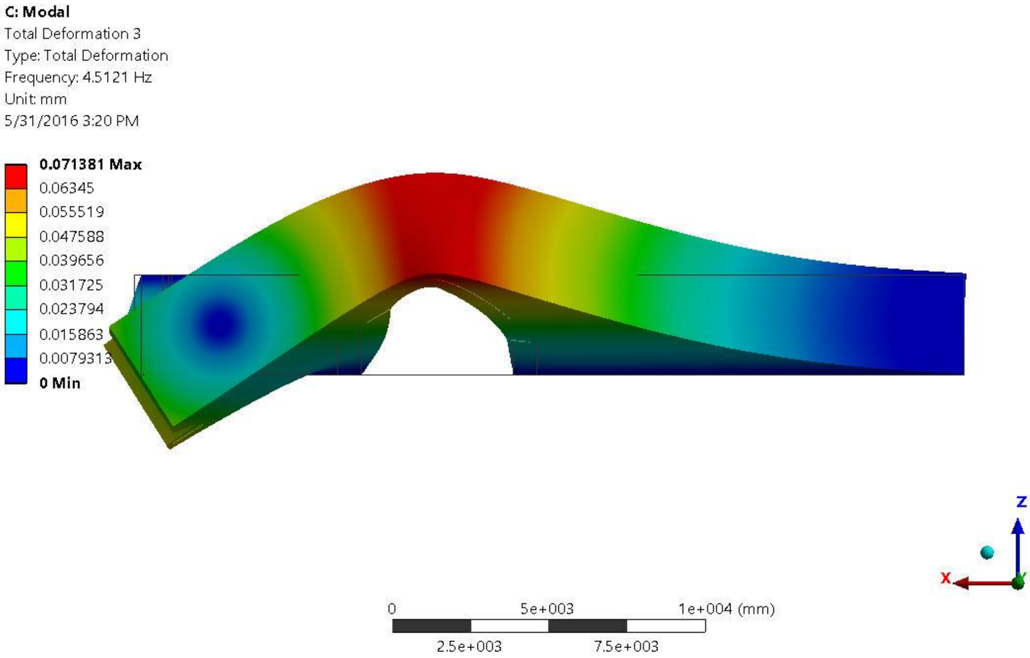
Appendix E27. Second mode shape of wall portion B on plan.



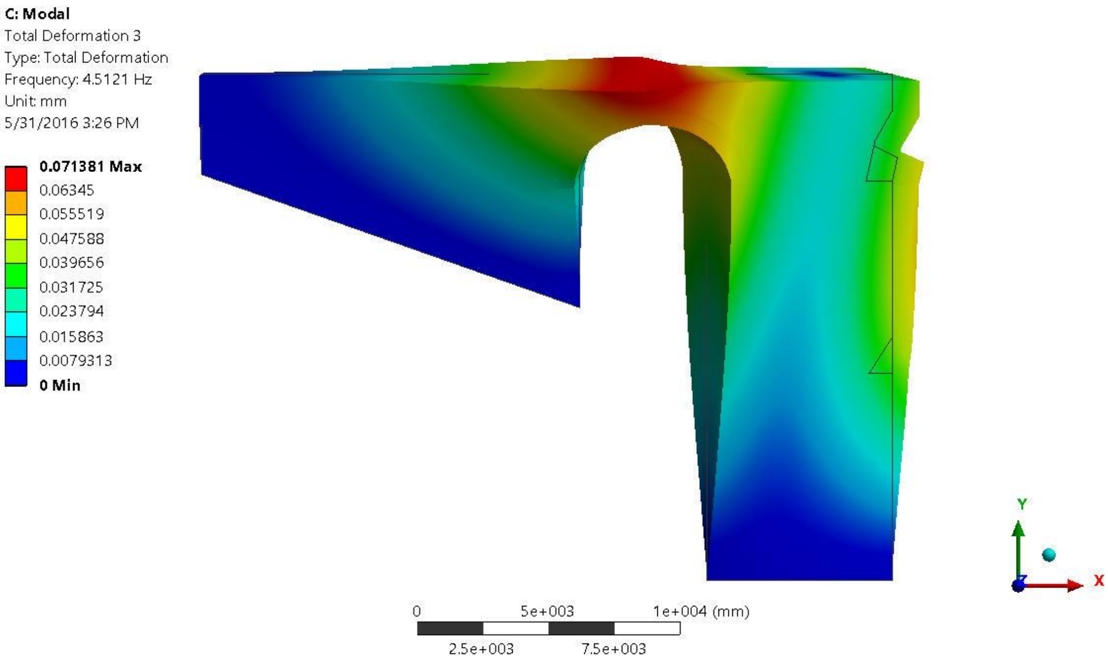
Appendix E28. Second mode shape of wall portion B on east elevation.



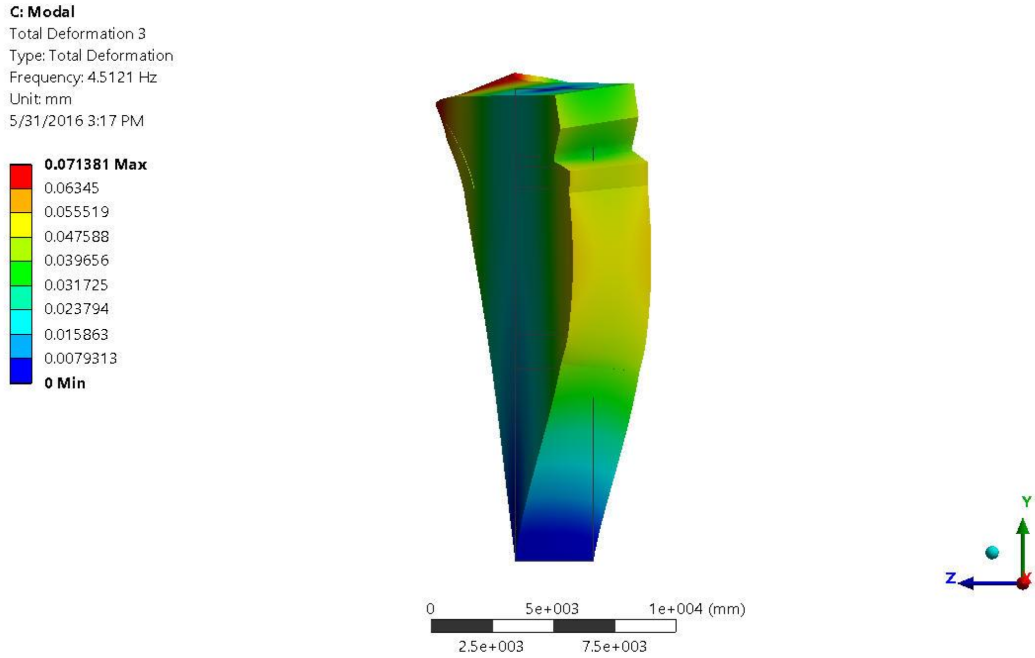
Appendix E29. Second mode shape of wall portion B at north end.



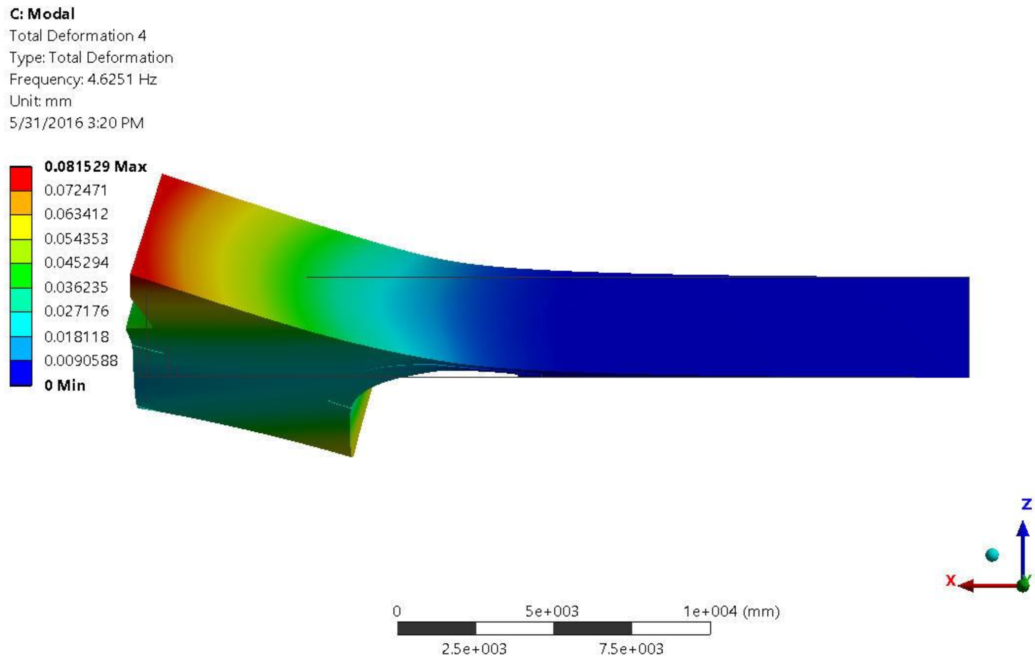
Appendix E30. Third mode shape of wall portion B on plan.



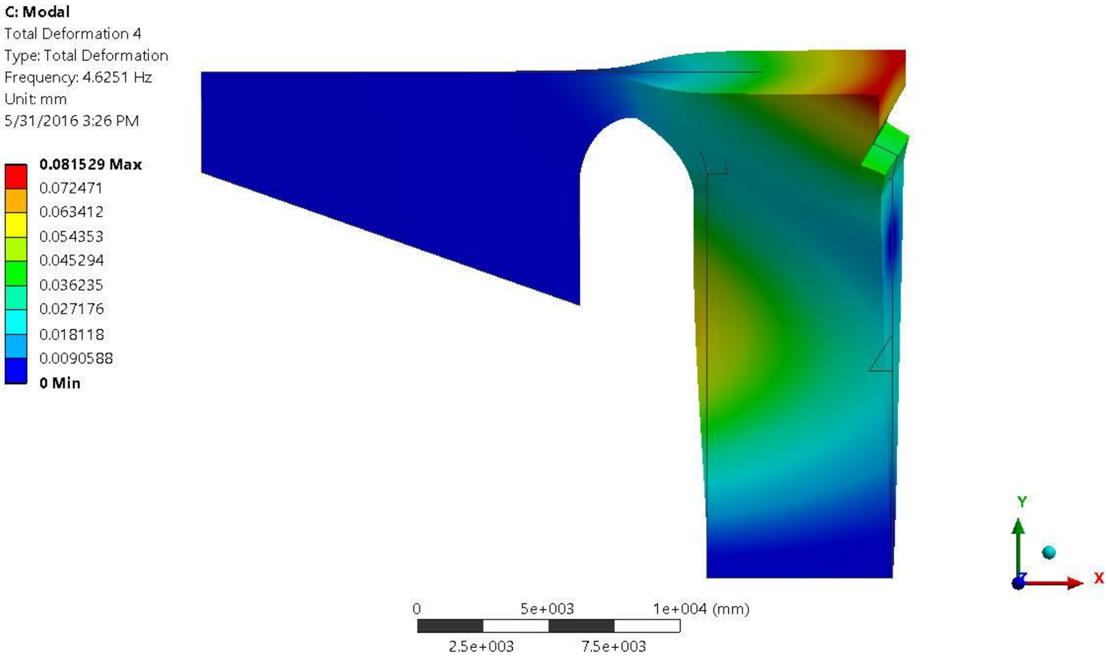
Appendix E31. Third mode shape of wall portion B on east elevation.



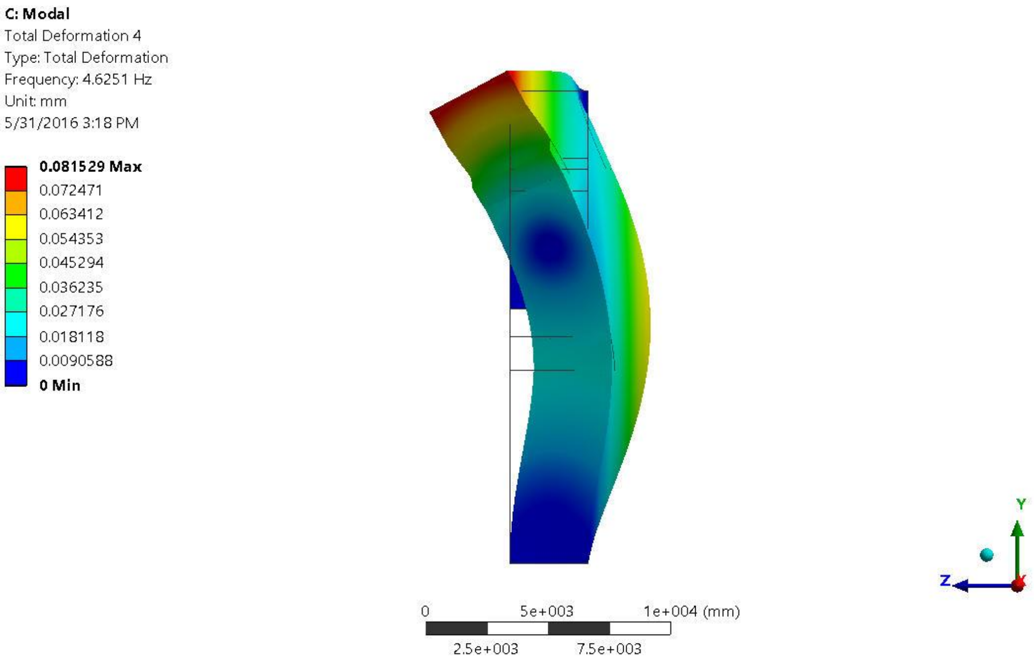
Appendix E32. Third mode shape of wall portion B at north end.



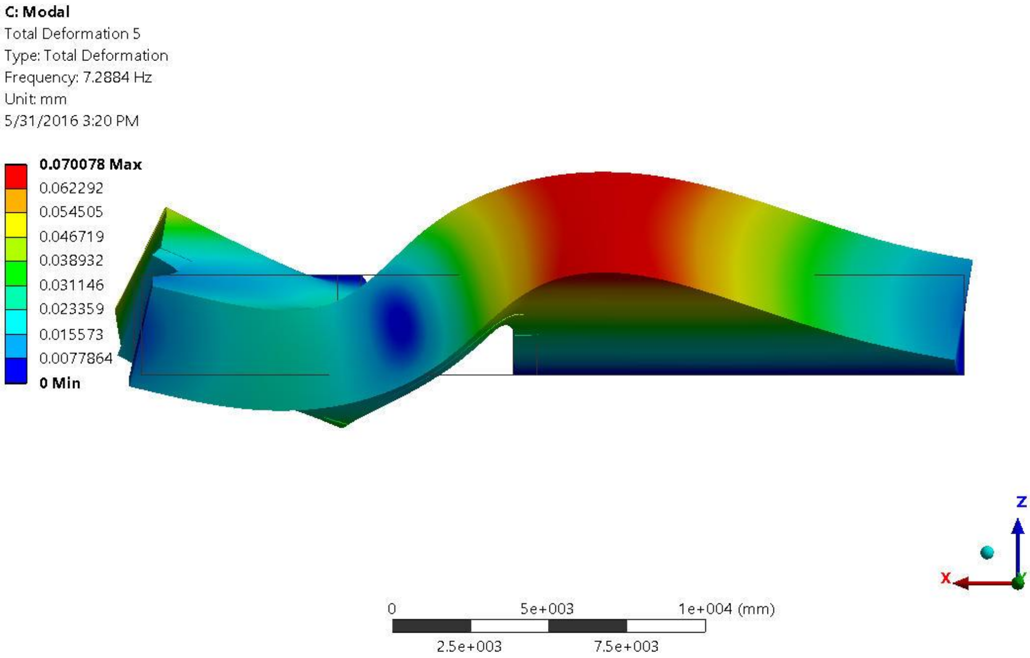
Appendix E33. Fourth mode shape of wall portion B on plan.



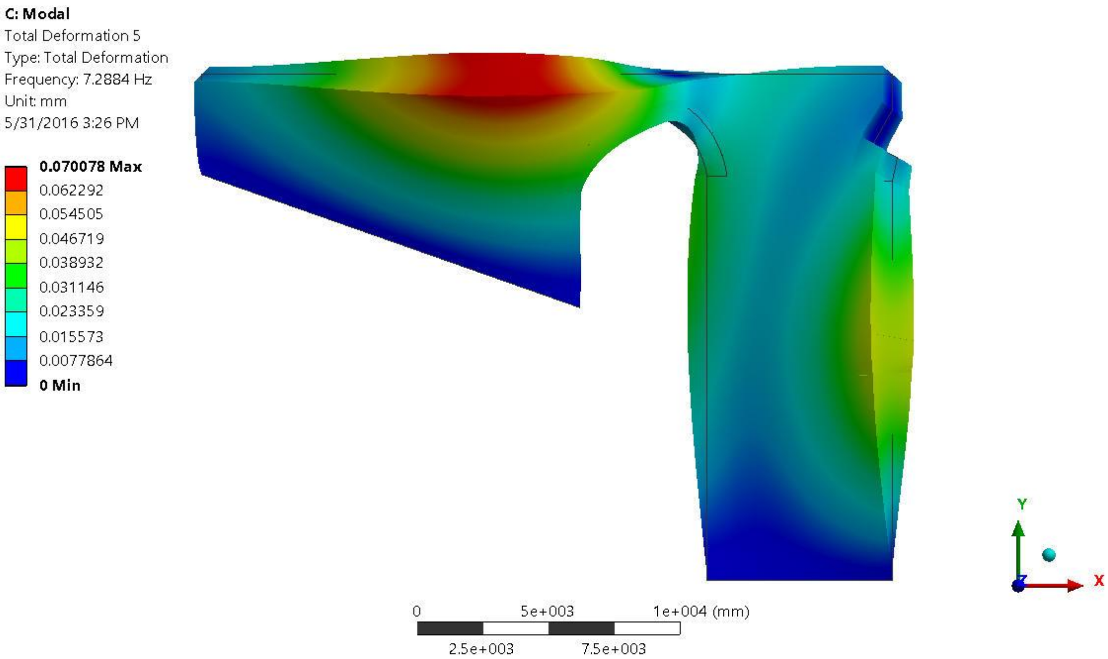
Appendix E34. Fourth mode shape of wall portion B on east elevation.



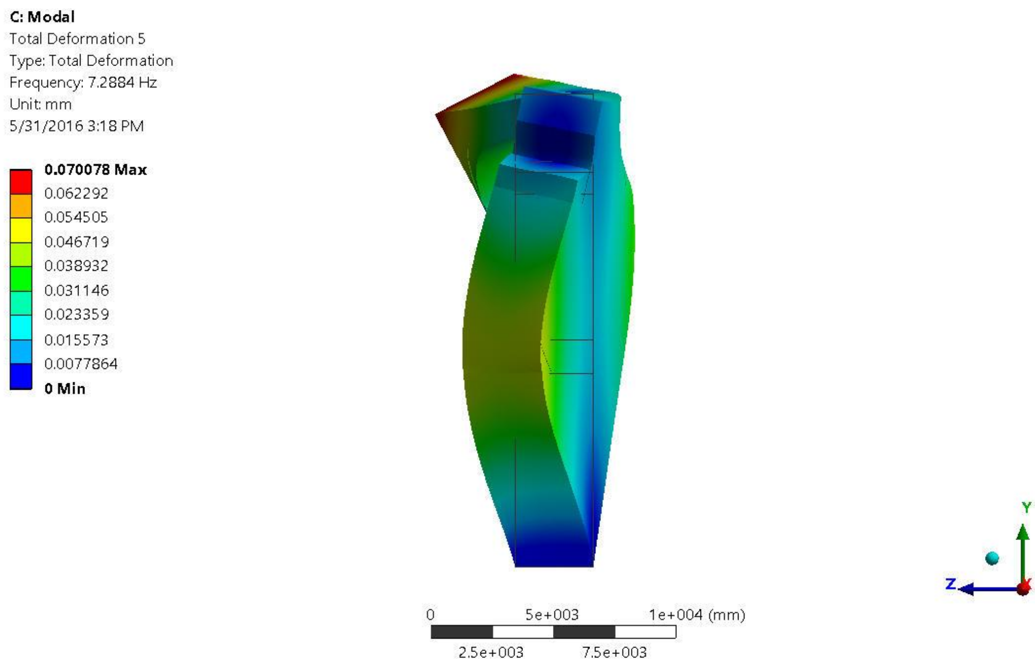
Appendix E35. Fourth mode shape of wall portion B at north end.



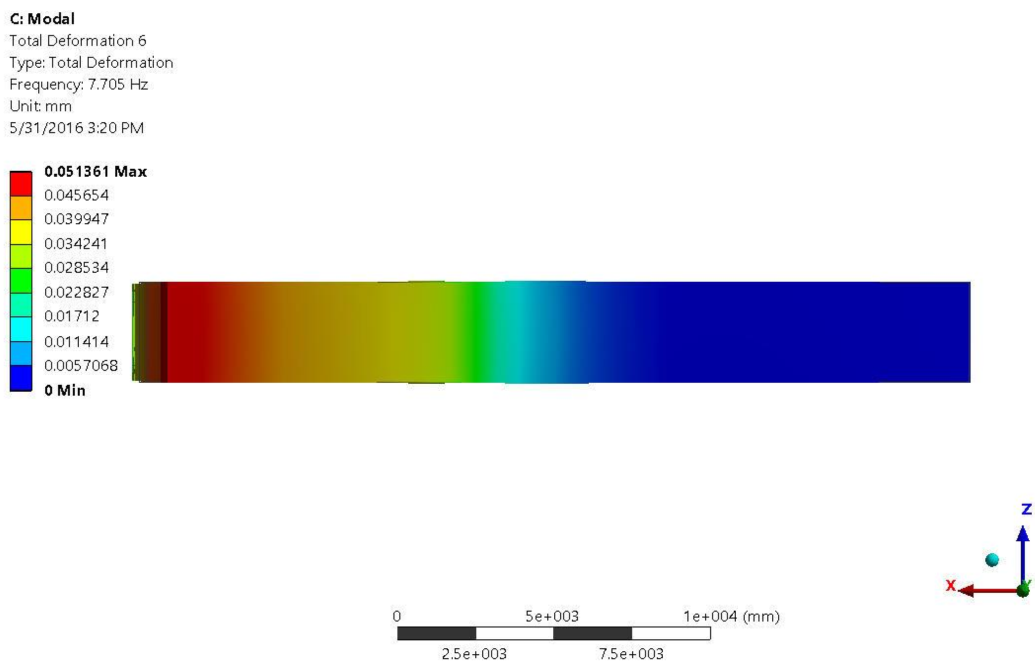
Appendix E36. Fifth mode shape of wall portion B on plan.



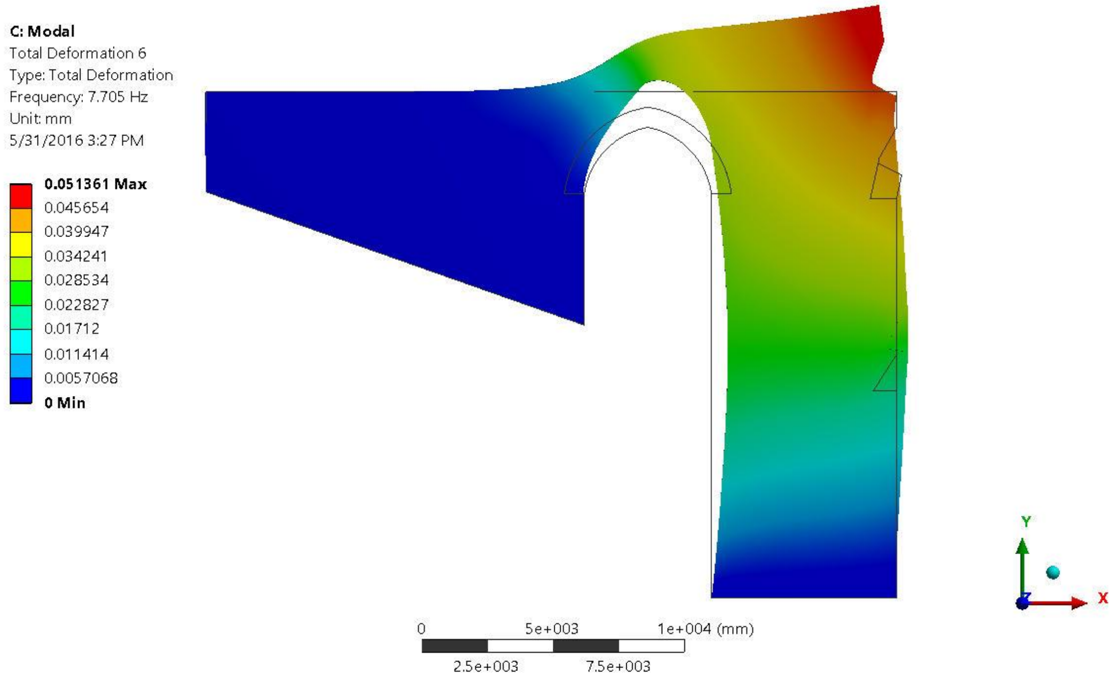
Appendix E37. Fifth mode shape of wall portion B on east elevation.



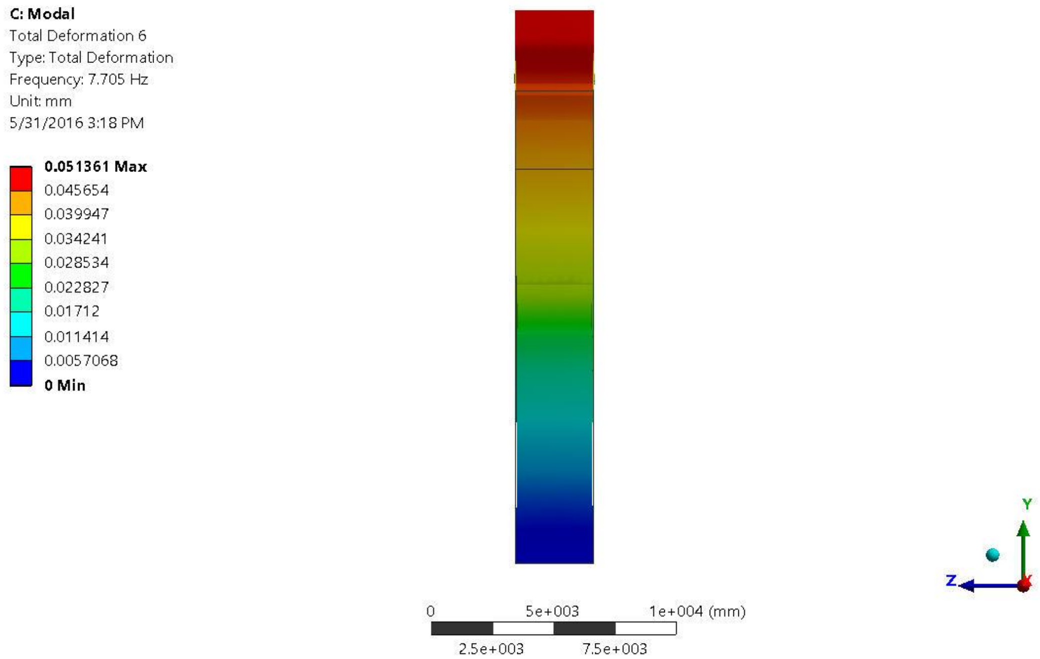
Appendix E38. Fifth mode shape of wall portion B at north end.



Appendix E39. Sixth mode shape of wall portion B on plan.



Appendix E40. Sixth mode shape of wall portion B on east elevation.



Appendix E41. Sixth mode shape of wall portion B at north end.

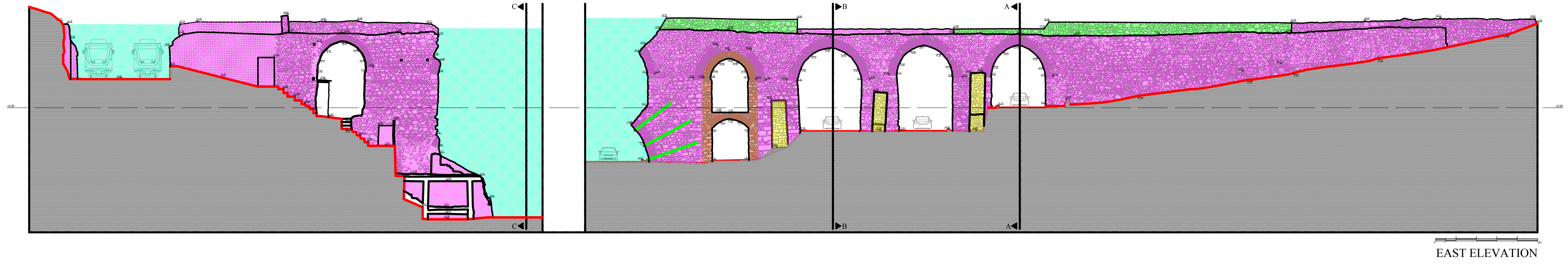
APPENDIX F

PERIOD ANALYSIS

PERIOD ANALYSIS

FIRST PERIOD Construction of the Aqueduct in 4th century BC	
SECOND PERIOD Construction of the Aqueduct in 1674	
THIRD PERIOD Construction of additional buttresses	
FOURTH PERIOD Construction of the second arch under the fourth arch from the northern end	
FIFTH PERIOD Demolishment of most of arches of the Aqueduct	
SIXTH PERIOD Construction of concrete duct	

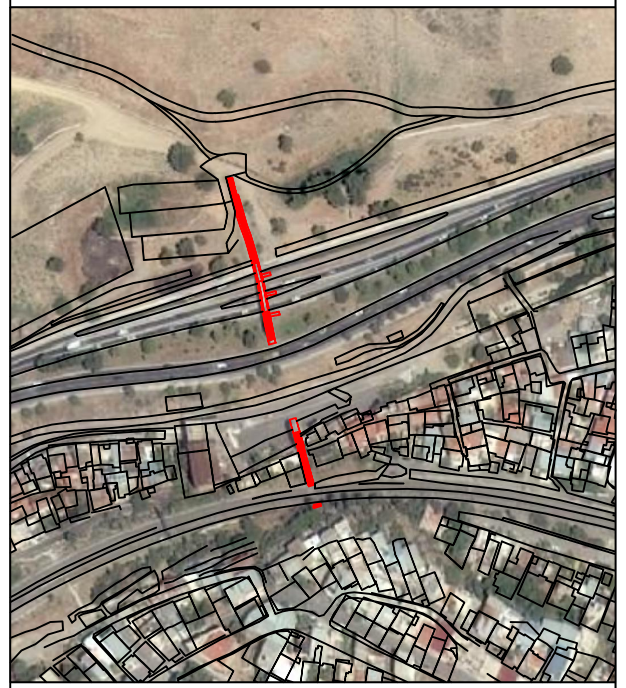
Appendix F1: Period Analysis



A THESIS Submitted to the Graduate School of Engineering and Sciences of İZMİR INSTITUTE OF TECHNOLOGY for the Degree of MASTER OF SCIENCE of ARCHITECTURAL RESTORATION

IDENTIFICATION OF
VEZİRAĞA AQUEDUCT IN İZMİR
AS A HISTORICAL MONUMENT

İzmir, 2016



Thesis by:
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Co-Supervisor:
Assoc. Prof Dr. Engin AKTAŞ

- [ ] METHODOLOGY
- [x] ANALYSIS
- [ ] MEASURED DRAWING
- [ ] RESTITUTION

PERIOD ANALYSIS

Appendix F2: Period analysis on East Elevation

APPENDIX G

RESTITUTION

TYPES OF SOURCES

Traces coming from the aqueduct	(red)
Old photographs	(orange)
Comparative study within the aqueduct	(cyan)
Written documents	(green)

RELIABILITY DEGREES

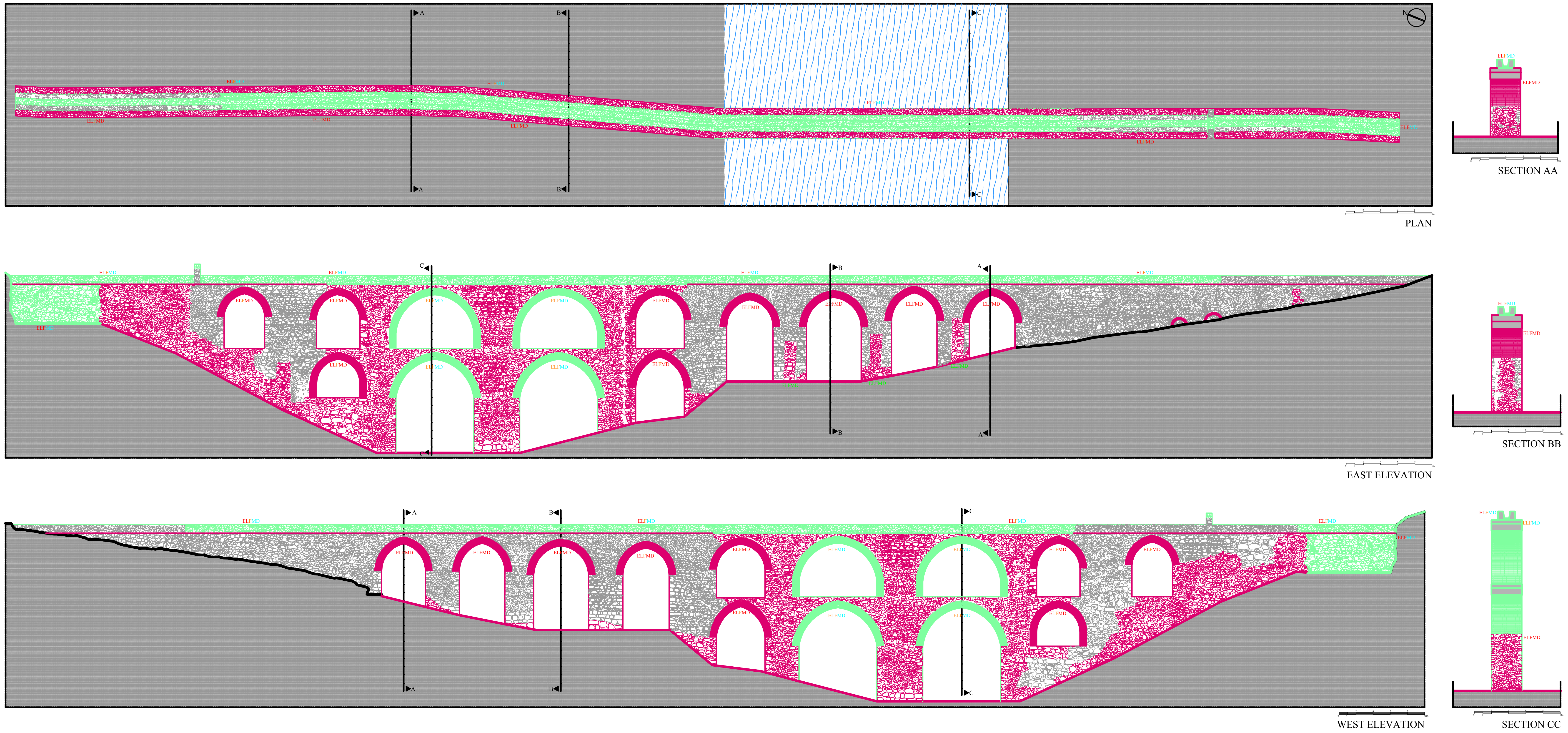
First Level

ELFMD
Remains of original arches at the south end of wall portion B and north end of wall portion C
The arch on wall portion C
The repaired brick - stone masonry arches on the south end of wall portion B
The original stones and bricks

Second Level

- ELFMD
  (The demolished part between wall portions B and C)
- ELFMD
  (The demolished stone duct)
- ELFMD
  (The demolished part on the railway)
- ELFMD
  (Nonexistence of buttresses on wall portion B)

Appendix G1: Sources and Reliability Degrees for Restitution



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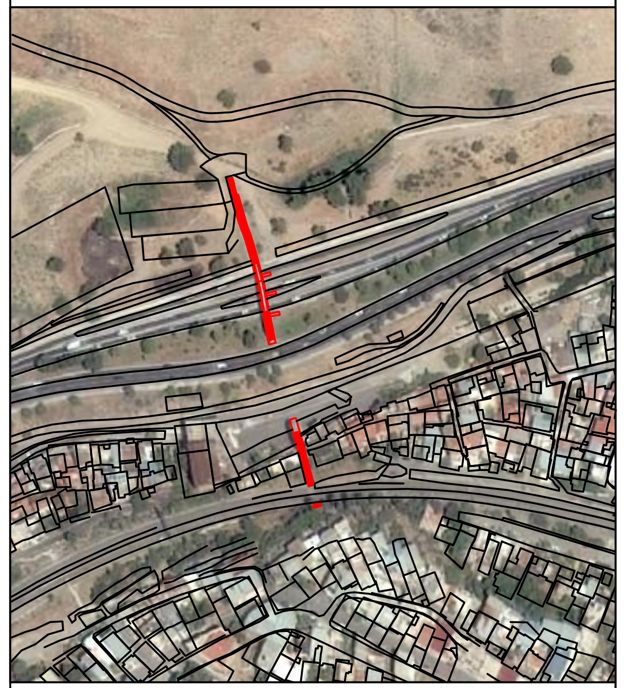

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- [ ] METHODOLOGY
- [ ] ANALYSIS
- [ ] MEASURED DRAWING
- [x] RESTITUTION

RESTITUTION
OF VEZİRAĞA AQUEDUCT

Appendix G2: Restitution