Conservation-Aimed Evaluation of a Historical Aqueduct in İzmir

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Abstract: The seventeenth century was the era in which İzmir became an international commercial center in the eastern Mediterranean. The vizier of the era, Köprülü Fazıl Ahmet Paşa, noticed the scarcity of potable water in relation with the increasing population at the center of this harbor city and ordered the construction of an aqueduct on Melez Valley. The Veziraăa Aqueduct was constructed in 1674. This article aims to identify historical, architectural, and structural characteristics of the Veziraăa Aqueduct so that its heritage values and conservations problems can be understood. The geographical and historical characteristics of the Veziraăa Aqueduct are described by taking the effects of site and the sociocultural situation of city into consideration. The architectural characteristics of the aqueduct are prepared by using the site survey data to reveal the current condition and find out the original state. Seismic behavior of the aqueduct is investigated by using two approaches: analytical equivalent static analysis and finite-element analysis. The historical, architectural, and structural characteristics of the Veziraăa Aqueduct prove its historical, documentary, and aesthetic values. **DOI: 10.1061/(ASCE)AE.1943-5568.0000353.**

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Introduction

The significance of objects, buildings, and sites may change over time. Riegl (1982) in his 1903 essay had referred to unintentional monuments: acquiring value during their life span because of historic significance. Stubbs (2009) refers to these monuments as cultural heritage sites with associative value and underlines the inevitability of understanding their history. The Veziraăa Aqueduct is a utilitarian structure that has become a monument in terms of its association with the history of İzmir city; the small town of İzmir had become an international trade center starting with the seventeenth century.

In 1674, the Veziraăa Aqueduct was built after the order of the Ottoman Vizier Köprülü Fazıl Ahmet Paşa as a part of the Veziraăa Water Transmission Line in order to fulfill the potable water necessity of the İzmir city center, which was rapidly developing as a harbor city of the Ottoman Empire, on the western coast of Anatolia, in Eastern Mediterranean with the border of the Aegean Sea.

On the other hand, studies focusing on the aqueduct as a heritage type within the content of cultural inventory of Turkey are limited. Academic studies are generally on İstanbul examples (Anabolu 2001; Salman 2008; Akova 2012). Nevertheless, there are some comprehensive works on water structures in the Turkish period in Anatolia (Aktepe 1976; Önge 1997; Geyik 2007).

Research on İzmir aqueducts mainly deals with their design in terms of an engineering work (Öziş et al.1999; Weber 2011). There is some information on historical evolution of İzmir aqueducts and water structures (Weber 2011; Laflı 2011; Ürer 2013). The Metropolitan Municipality of İzmir has recently included the Veziraăa Aqueduct in its restoration program.

The aim of this study is to identify historical, architectural, and structural characteristics of the Veziraăa Aqueduct in İzmir in order to provide a basis for its conservation as a monument. There has been a literature review of the case study itself, documentary and analytic studies on aqueducts in general, a measured survey for 1:50 scale documentation with tacheometric techniques, visual analysis and mapping, seismic assessment, historical research and comparative study, and evaluation. The tools used were Total Station, Adobe Photoshop CS6, AutoCAD, MATLAB, and ANSYS software.

Geographical Characteristics

İzmir is situated around İzmir Bay, a natural harbor protected by the Urla Peninsula, dividing the Aegean Sea into northern and southern halves. The aqueduct is at the south end of the bay.

The geographic components of the site within which the aqueduct is located are Mount Kadifekale (the Velvet Castle, the antique Pagos) at the north, skirts of Mount Nif at the south, and the Yeşil brook-valley (St. Anna Valley) system in between them. Kadifekale crowns the site as well as the city of İzmir with its 186 m of height (Fig. 1). The typical Mediterranean coast is observable (Eliçalışkan 2014).

The site is in the first-degree earthquake zone (AFAD 1996). After the construction of the aqueduct, eight significant earthquakes took place in the center of İzmir (Table 1). They probably had damaging effects on the aqueduct (Biro 2000). As the recorded fatalities (Fig. 2) described changes in topography and its closeness in distance to the studied site indicated, the 1688 earthquake, which took place just after the construction of the aqueduct, must have damaged the structure (Fig. 3).

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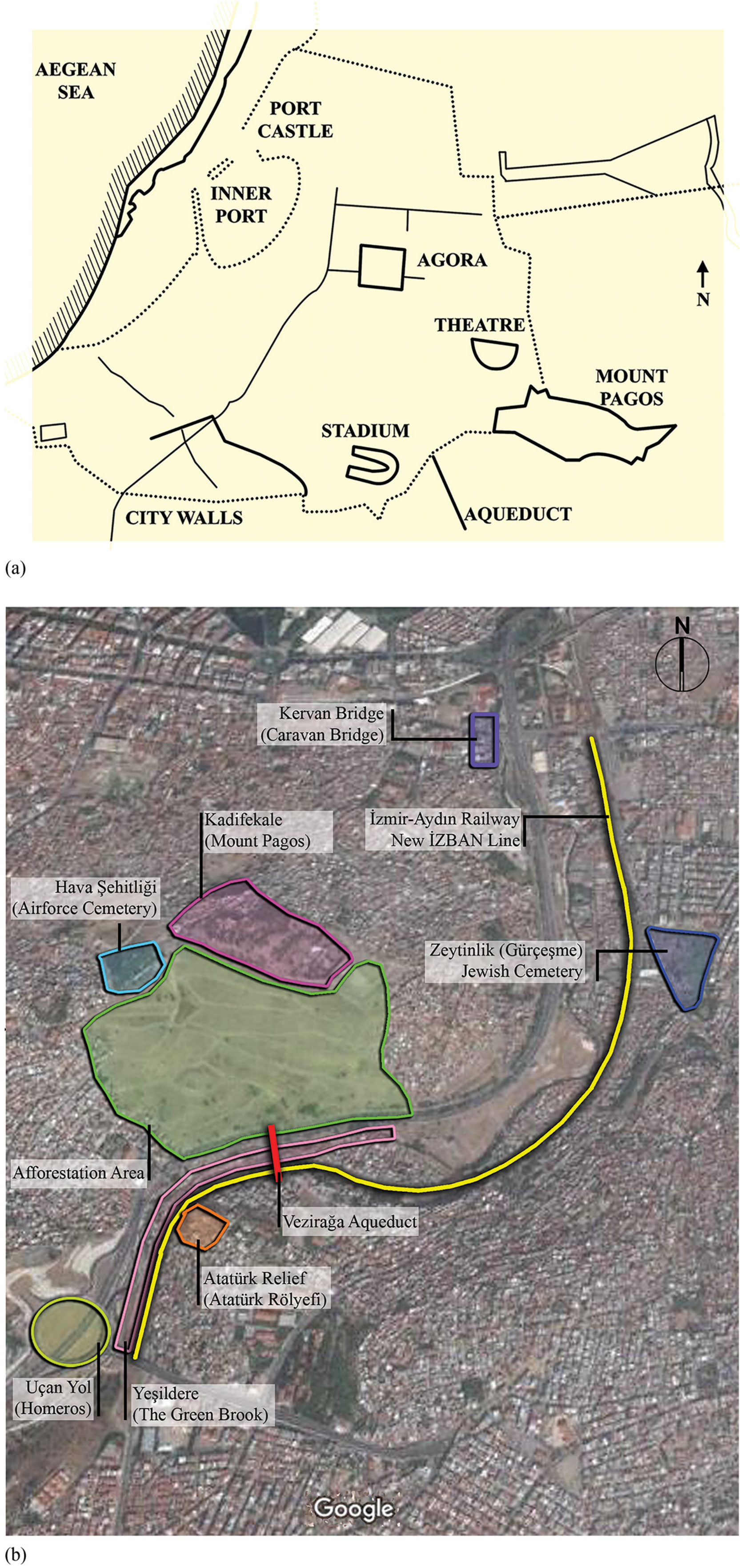

Fig. 1. (a) Historical Center of İzmir (adapted from Yılmaz and Yetkin 2003); and (b) present site of the aqueduct (map data © 2019 Google).

Identification of the Veziraǧa Aqueduct

Historical Characteristics

İzmir has been settled by the natives of Anatolia since the Neolithic era. After its initial foundation on the Bornova plain at the east of the bay (Derin 2016), it was resettled on a peninsula at the northeast (Akurgal 2014), which is known as Bayraklı today. The third İzmir (Smyrna) was founded between Kadifekale and the southern coast of the bay in the fourth century BC. Since then, this site has been continuously settled by various civilizations (Yılmaz and Yetkin 2003).

Table 1. Historical earthquakes that could have damaged the aqueduct

Date	Location	Magnitude (Ms)	Number of fatalities	Number of damaged buildings
10-07-1688	İzmir	—	15,000	—
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
12-16-1977	İzmir	5.5	—	40

Source: Data from KOERI (2010).

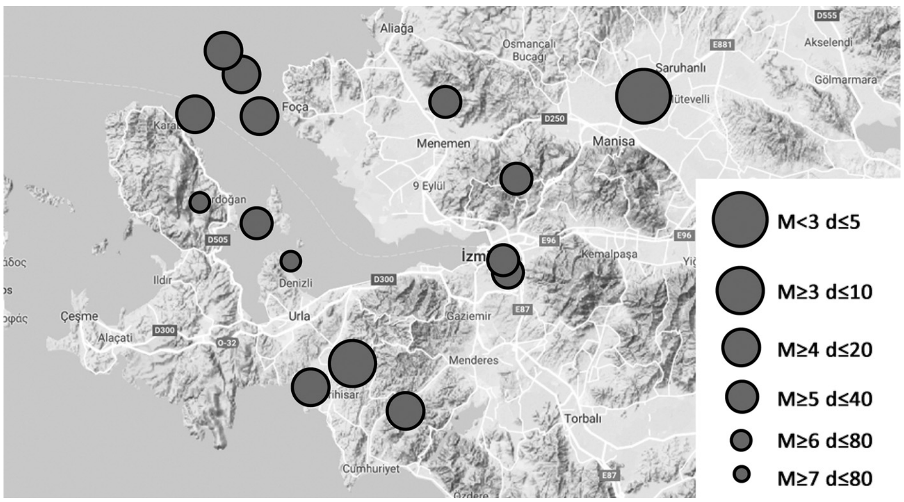

Fig. 2. Earthquakes 50 km radius from İzmir city center since 1900. (Reprinted with permission from KOERI 2010.)

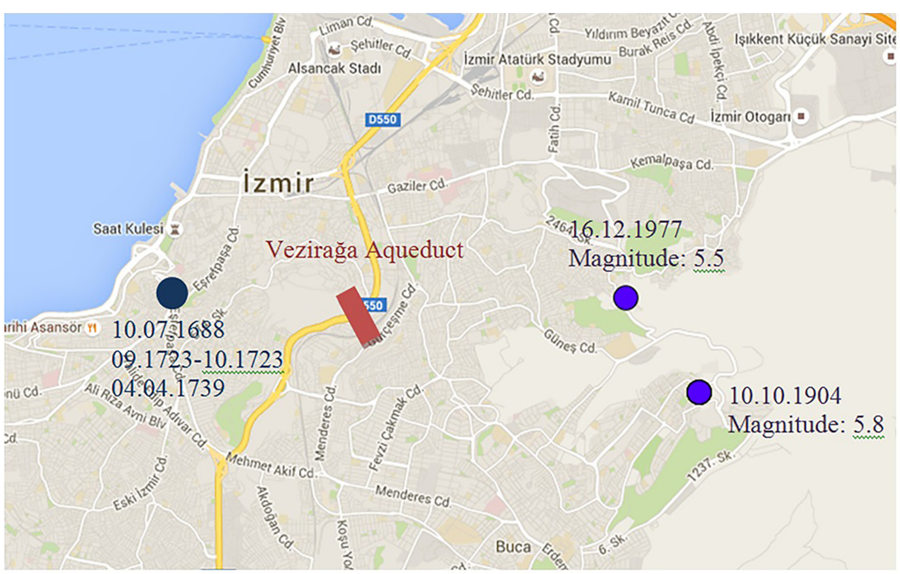

Fig. 3. Map of important earthquakes close to the Veziraǧa Aqueduct. (Reprinted with permission from KOERI 2010.)

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Potable water, necessary for the third settlement at the southeast of the bay, was provided from the springs at the skirts of Mount Nif at the east and on the plateau of Seydiköy at the south. From these positions, which were relatively high compared to the settlement between the castle and the coast, water could run down naturally. For the districts close to the castle, the Karapınar waterline, whose spring was up in the Mount Nif, was established as a high-pressure water transmission line (Weber 2011). There are observations of Western travelers on these waterlines (Pococke 1743; Chandler 1825; Arundell 1834; Hamilton 1842; Storari 1857; Weber 2011).

They have recorded six historical water transmission lines (Fig. 4). The majority (five of six) have their roots in Roman or Byzantine eras (Weber 2011). The only water transmission line whose exact dating can be made is Vezirağa, which is from the Turkish period (one of six) (Weber 2011; Öziş et al. 1999; Topçu 2010). The Ottoman Vizier Köprülü Fazıl Ahmet Paşa donated money for the construction of the Vezirağa Potable Water Transmission Line in 1674 (Topçu 2010). The line (Fig. 4) is composed of the spring in the vicinity of the Şirinyer train station, a water channel, 57 fountain (this number is recorded as 73 in older research) (Arundell 1834; Ülker 1994; Weber 2011). Topçu's (2010) examination is based on the related foundation charters, new fountains (Topçu 2010), 10 restored fountains (Arundell 1834; Ülker 1994; Weber 2011), and an aqueduct (Öziş et al. 1999; Weber 2011).

The water channel, which is 0.6 m in width and supported with side walls (Öziş et al. 1999), is positioned at the lowest level in the Yeşil (Melez) Valley in comparison to the other waterlines, including the Byzantine one in the vicinity, in order to gather the water of all possible sources (Weber 2011). It generally runs in the form of an underground gallery and can be observed in a few locations (Fig. 5).

Between 1858 and 1860, the portion of the İzmir-Aydın railway in Yeşil Valley was constructed (Atila 2002) (Fig. 6), and it has made a gap in the aqueduct at its south end.

The central portion of the aqueduct collapsed in a spate in 1931 (Akyüz Levi 2009). Yeşildere Highway was constructed in 1984 in place of the narrow caravan road running parallel to the brook at its north. The aqueduct was listed as cultural heritage on January 17, 1975, by the Supreme Council for the Immovable Antiquities and Monuments with the Decision Number 152 according to the information taken from İzmir First Regional Directorate of Conservation of Cultural Assets.

On May 10, 2007, a buffer zone was defined around the aqueduct in order to preserve its silhouette by İzmir Number 1 Regional Board for the conservation of Cultural and Natural Assets with the decision numbered 2312. In 2012, illumination of the aqueduct was realized.

Physical Characteristics

The Vezirağa Aqueduct today has three portions, which are referred to as A, B, and C, from north to south, respectively (Fig. 7).

Portion A is a stone masonry wall (3.20 m in width, 81.30 m in length), perforated with five brick arches, and has a duct on its top (Fig. 8). The first, second, third, and fourth arches are two-centered (bicentric), while the fifth arch has one center. On the east facade of Portion A, there are three additional buttresses constructed with stone. The southern arch is reinforced with additional two arches, one on top of the other. The remains of the sixth arch are seen at the south end of this portion. Portion B (3.20 m in width, 26.30 m in length) is a stone masonry wall with a single brick arch on the present stream bed. There are remains of two arches one on top of the other at the north end of Portion B. Portion C (3.20 m in width,

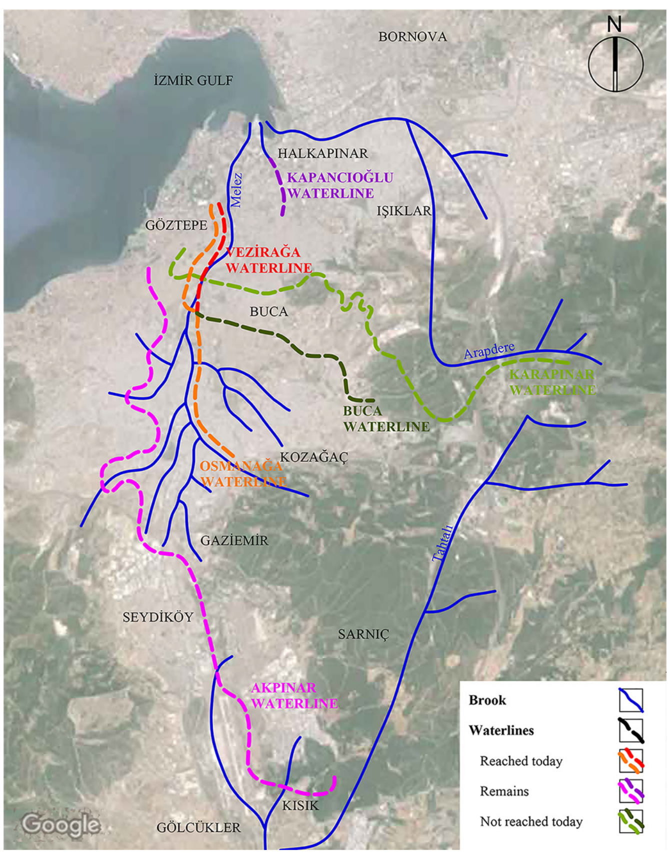

Fig. 4. Historical waterlines and brooks in İzmir. (Reprinted with permission from Öziş et al. 1999; Weber 2011; map data © 2019 Google.)

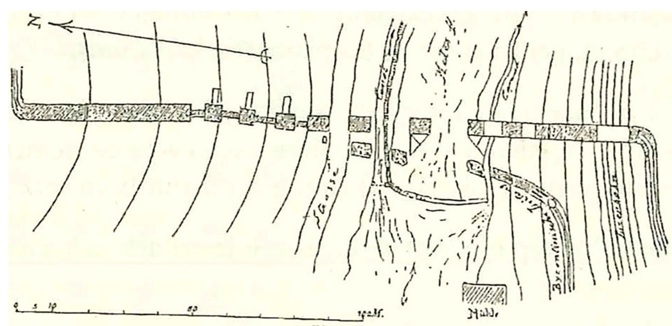

Fig. 5. Site plan in 1899. (Reprinted with permission from Weber 2011.)

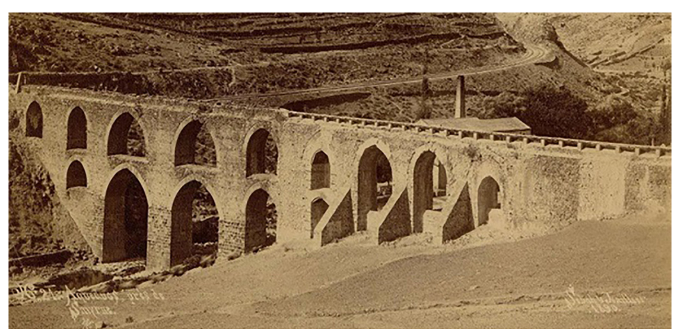

Fig. 6. View of east facade with buttresses in 1890. (Reprinted from IBB 2015.)

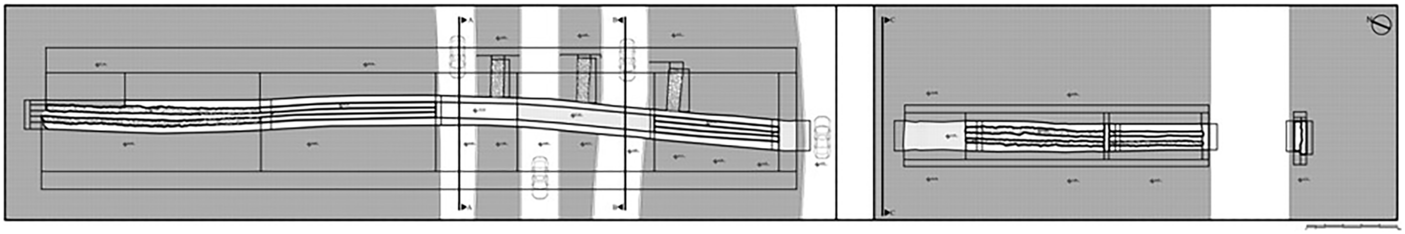

Fig. 7. Plan of the aqueduct.

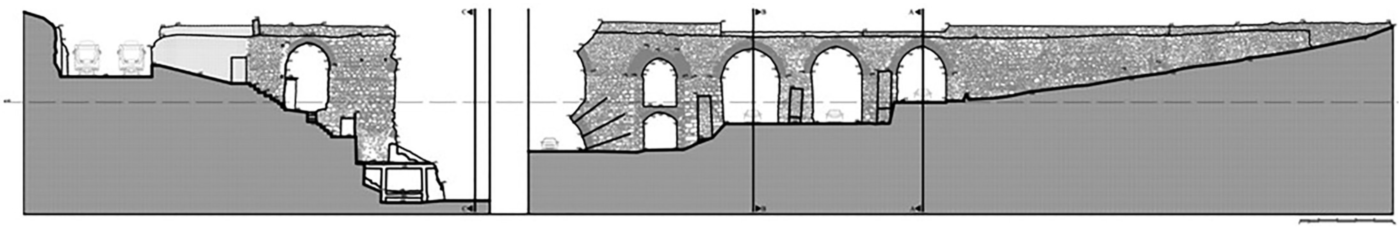

Fig. 8. East elevation of the aqueduct.

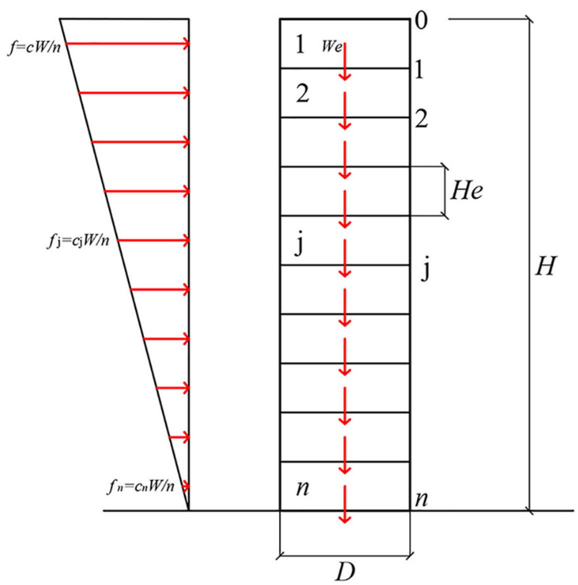

Fig. 9. Lateral loading condition of the pier.

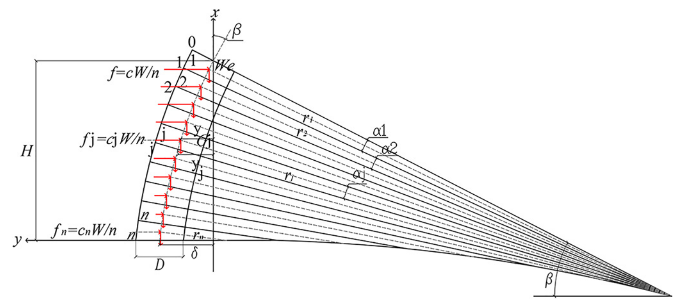

Fig. 10. Deformed shape of the pier under its own weight and the lateral eccentric loads.

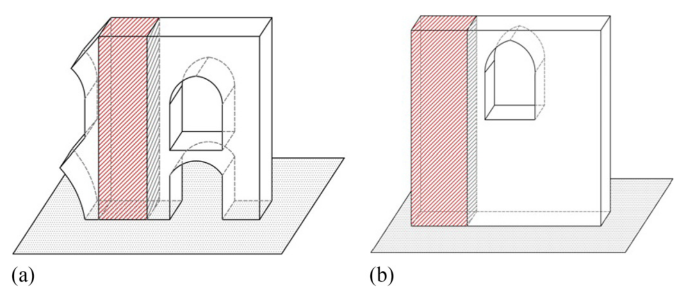

Fig. 11. Determination of the pier of (a) Portion A; and (b) Portion B to use during the out-of-plane seismic analysis.

1.00 m in length) is just next to the railway and rests on the rocky terrain at its north end. This portion is almost in ruins. Only traces of the stone duct are seen.

Three types of structural failures are observed at the aqueduct: demolishment, out-of-plumbness, fractures. The parts between Portion A–B and Portion B–C—88 m from the northern end with 40 m length and 154 m from the northern end with 9 m length—were demolished. Portion A leans to the east direction (2°), and portion B leans to the west direction (1°). Three different types of fractures are observed as horizontal, vertical, and diagonal on the stone masonry wall and on the brick arches. These failures jeopardize the stability of the wall and have caused loss of structural integrity.

Seismic Evaluation of the Aqueduct

The Vezirağa Aqueduct might be at risk of collapse from a probable future moderate earthquake because İzmir is classified as a first-degree earthquake zone according to the Turkish Seismic Design Code (Ministry of Public Works and Settlement 2007). The expected effects of a future earthquake on a structure can be investigated starting from the determination of structural characteristics.

The structural analysis of a structure under earthquake loads can be carried out either using equivalent static analysis or dynamic analyses. Equivalent static analysis is preferred to transform the seismic load, which is dynamic in nature, to a static equivalent lateral load mostly influenced by the first natural vibration period of the structure. The analyses are applied to obtain seismic resistance of a historical structure, and the results are used for structural intervention decisions. Both static and dynamics analyses are used to investigate the seismic behavior. Since the structure is considerably stiff along the longitudinal direction, the out-of-plane resistance is evaluated using an easy-to-apply numerical model represented by La Mendola and Papia (1993) and used first.

In this model, a wall portion or a pier is represented (Fig. 9). The pier has been divided into n number of elements along the height. 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 $W = BDH\gamma$, where B = width of the pier; D = depth of the pier; H = height of the pier; and γ = density of stone masonry material. The elements have the weight of $W_e = W/n$. The horizontal inertia force applied on one piece is stated with f_j, where j defines the number of elements. f_j is linked with W_e and c_j, which is the seismic coefficient to identify the intensity of earthquake loading (Fig. 9).

$$f_j = c_j(W/n) = c[(n-j+1/2)/(n-1/2)](W/n)$$

The expected deformed shape was drawn to calculate the maximum seismic coefficient and the maximum deflection (Fig. 10).

The slenderest parts of Portions A and B (Fig. 11; Table 2), which are the highest piers, were selected to be analyzed. The piers were assumed, as they were fixed to the ground, to be free at the top

Table 2. Constant data of stone masonry of Portions A and B of the Veziraĝa Aqueduct

Physical features	Portion A	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 (no effect on procedure, taken as 1)	3.30 m (no effect on procedure, taken as 1)
Density of stone masonry (γ)	21 $kN{\cdot}m^{3}$ [a]	21 $kN{\cdot}m^{3}$ [a]
Modulus of elasticity (E)	870 to 1,500 MPa[a]	870 to 1,500 MPa[a]
Discretization parameter (ε)	0.2072	0.2015
Acceleration of gravity (g)	9.81 m/s^2	9.81 m/s^2

[a]Data from Ercan and Nuhoğlu (2014); Nohutçu et al. (2015).

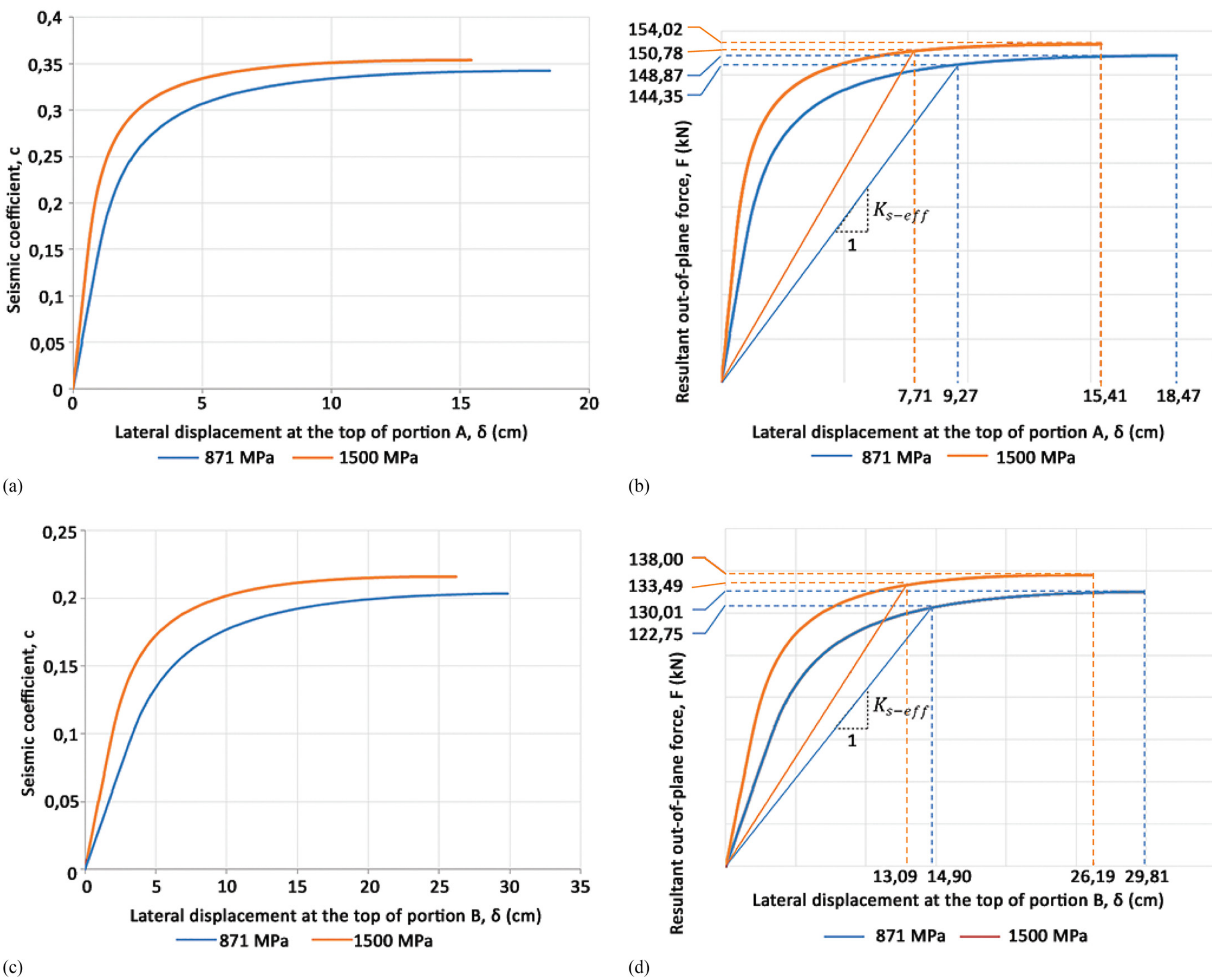

Fig. 12. (a) Curve of c–δ for wall Portion A; (b) curve of c–δ for wall Portion B; (c) curve of F–δ for wall Portion A; and (d) curve of F–δ for wall Portion B.

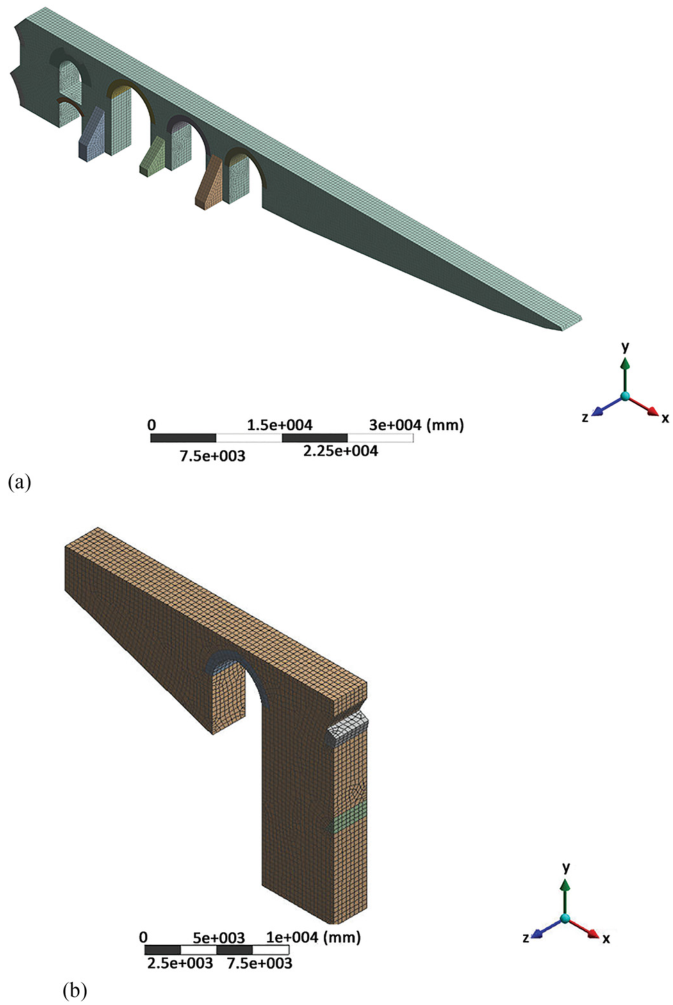

Fig. 13. (a) Finite-element model of Portion A; and (b) finite-element model of Portion B.

Table 3. Material characteristics 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)	870 to 1,500	201
Shear modulus	326	80.4
Density (kg/m^3)	2,100	1,750
Poisson ratio	0.34	0.25

Source: Data from Ercan and Nuhoğlu (2014); Nohutçu et al. (2015).

and strong enough for any compressive forces with no-tension material.

Under these circumstances, their own weight and increasing lateral eccentric loads were applied on the structure to determine the resistance of the aqueduct against the out-of-plane forces. The number of pieces was identified by the calculation of the discretization parameter (dimensionless height of the pieces) $\varepsilon = H/nD = H_e/D$. The discretization parameter should be between 0.20 and 0.25 to have the appropriate results from the numerical model. According to the calculations, the piers were divided into 19 pieces for Portion A and 29 pieces for Portion B (Table 2).

The piers behaved as linear elements at the beginning and became nonlinear after the first crack during the loading. Maximum seismic coefficients and deflections for both piers have been calculated following the procedure presented in Gürel et al. (2010) and La Mendola and Papia (1993), and corresponding curves are presented in Fig. 12. By the calculation of the effective secant stiffness (Fig. 13) of both piers, the natural periods of piers are calculated. When the piers meet with the first crack, they behave like a nonlinear element until the maximum value of $c_{(\max_A)} = 0.342396$ and $c_{(\max_B)} = 0.20335$ (870 MPa Young's modulus) and $c_{(\max_A)} = 0.35424$ and $c_{(\max_B)} = 0.21586$ (1,500 MPa Young's modulus). While the seismic coefficient has the maximum value, the deflections are $\delta_{(\max_A)} = 18.5\,\mathrm{cm}$ and $\delta_{(\max_B)} = 29.8\,\mathrm{cm}$ (870 MPa Young's modulus) and $\delta_{(\max_A)} = 15.41\,\mathrm{cm}$ and $\delta_{(\max_B)} = 26.19\,\mathrm{cm}$ (1,500 MPa Young's modulus). The piers reach to their maximum lateral resistance. The effective natural periods of the piers are obtained as $T_{(s-\mathrm{eff})A} = 1.28\,\mathrm{s}$ and $T_{(s-\mathrm{eff})B} = 2.17\,\mathrm{s}$ (870 MPa Young's modulus), and $T_{(s-\mathrm{eff})A} = 1.11\,\mathrm{s}$ and $T_{(s-\mathrm{eff})B} = 1.92\,\mathrm{s}$ (1,500 MPa Young's modulus). The overturning accelerations are found out as $a_{(0_A)} = 0.23\,\mathrm{g}$ and $a_{(0_B)} = 0.14\,\mathrm{g}$ (870 MPa Young's modulus) and $a_{(0_A)} = 0.24\,\mathrm{g}$ and $a_{(0_B)} = 0.15\,\mathrm{g}$ (1,500 MPa Young's modulus).

The dynamic behavior of a structure can be represented by its dynamic characteristics, such as natural frequencies of the oscillations and the mode shapes. Dynamic characteristics of the structure can be obtained by operational or experimental modal analysis and numerical simulations. In this study, a three-dimensional (3D) finite-element program, ANSYS, was used to

Table 5. Frequencies of finite-element model for Portion B

	Frequency (Hz)	
Mode	ANSYS model (1,500 MPa)	ANSYS model (870 MPa)
1	1.951	1.500
2	5.776	4.525
3	6.249	4.814
4	6.487	4.968
5	10.168	7.817
6	10.787	8.262

Table 4. Comparison of frequencies of Portion A with the analytical and experimental results of Ercan and Nuhoğlu (2014)

	Frequency (Hz)			PP method (Hz)[a]		SSI method (Hz)[a]	
Mode	ANSYS model (1,500 MPa)	ANSYS model (870 MPa)	Analytical modal parameters[a]	Test 1	Test 2	Test 1	Test 2
1	2.704	1.956	2.877	2.769	2.778	2.758	2.758
2	4.244	3.102	4.205	4.513	4.542	4.556	4.52
3	5.227	3.926	5.555	5.412	5.405	5.39	5.375
4	5.503	4.022	5.83	6.198	6.149	6.08	6.099
5	7.173	5.239	7.367	—	7.035	—	7.015
6	8.969	6.553	—	—	—	—	—

[a]Data from Ercan and Nuhoğlu (2014).

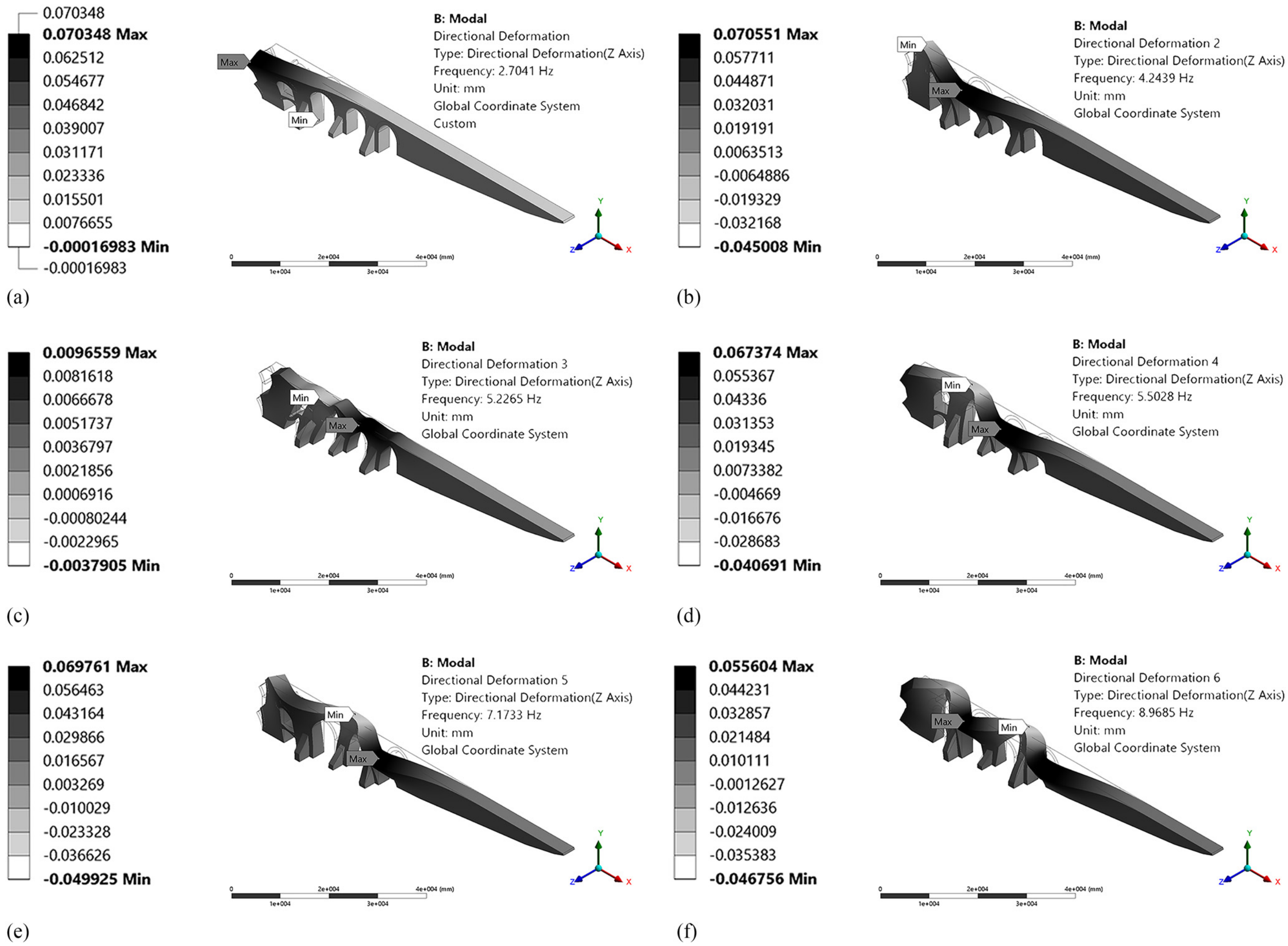

Fig. 14. Six mode shapes of Portion A: (a) directional deformation; (b) directional deformation 2; (c) directional deformation 3; (d) directional deformation 4; (e) directional deformation 5; and (f) directional deformation 6.

obtain the dynamic response of the Veziraǧa Aqueduct. The geometry of the two portions of the structure, A and B, was modeled separately (Fig. 13). Automatic mesh generation resulted with SOLID 186 and SOLID 187 elements. These elements are high-order 3D elements, with 20 nodes and 10 nodes where each node has three translational degrees of freedom. Mesh size is defined as 400 mm. The mesh consists of 170,733 nodes and 44,793 elements in total for Part A, and 64,926 nodes and 15,512 elements for Part B. All the degrees of freedom are restrained at the base of the structure; in other words, the structure is restrained at the ground level.

The Veziraǧa Aqueduct can be classified into two groups based on the element types: brick masonry arches and a stone masonry wall system, including the buttresses. According to that, two material types, brick masonry and stone masonry, were introduced into the model. The arches were modeled with brick materials. The stone masonry wall system was modeled with stone elements. In order to achieve a simpler model, out-of-plumbness and the other visible failures were not taken into account.

Stone masonry and brick masonry walls are composite structures. Bedon et al. (2016) conducted finite-element analyses of the dynamic response of a bridge structure and demonstrated that the response can change drastically with changing boundary conditions and material properties.

Ercan and Nuhoǧlu (2014) conducted a numerical and an operational modal analysis study on the Veziraǧa Aqueduct, Portion A. Nondestructive and destructive tests were conducted to obtain the material properties of stone and brick material. On the other hand, mortar properties are obtained from the literature. Ercan and Nuhoǧlu (2014) reported the stone wall material as pink and gray andesite stones. Young's moduli of the stone masonry and brick masonry were obtained according to the procedure proposed by Lourenço et al. (2001). Measured and calculated material properties are available in Table 3. In the scope of the study, numerical and experimental analysis results were reported. A numerical model was constructed with the material properties given in Table 3. Dynamic characteristics of the structure have been extracted by utilizing operational modal analysis with a peak-picking method and Stochastic Subspace Identification method. Ercan and Nuhoǧlu (2014) calibrated the numerical model by using the experimental results.

In a more recent study, Nohutçu et al. (2015) conducted experimental and numerical analyses of the dynamic response of a historical masonry mosque, located in Manisa, Turkey. Stone masonry material was reported as pink and gray andesite stones and mortar with a Young's modulus value of 1,500 MPa. On the other hand, Ramos et al. (2010) conducted a similar study on a historical clock tower in Portugal. The stone material was reported as large granite stones and rubble stone with thick lime mortar joints. Ramos et al. (2010) accepted a heterogeneity in Young's modulus values of the stone elements. Corresponding Young's modulus values were reported between 0.8 and 6 GPa.

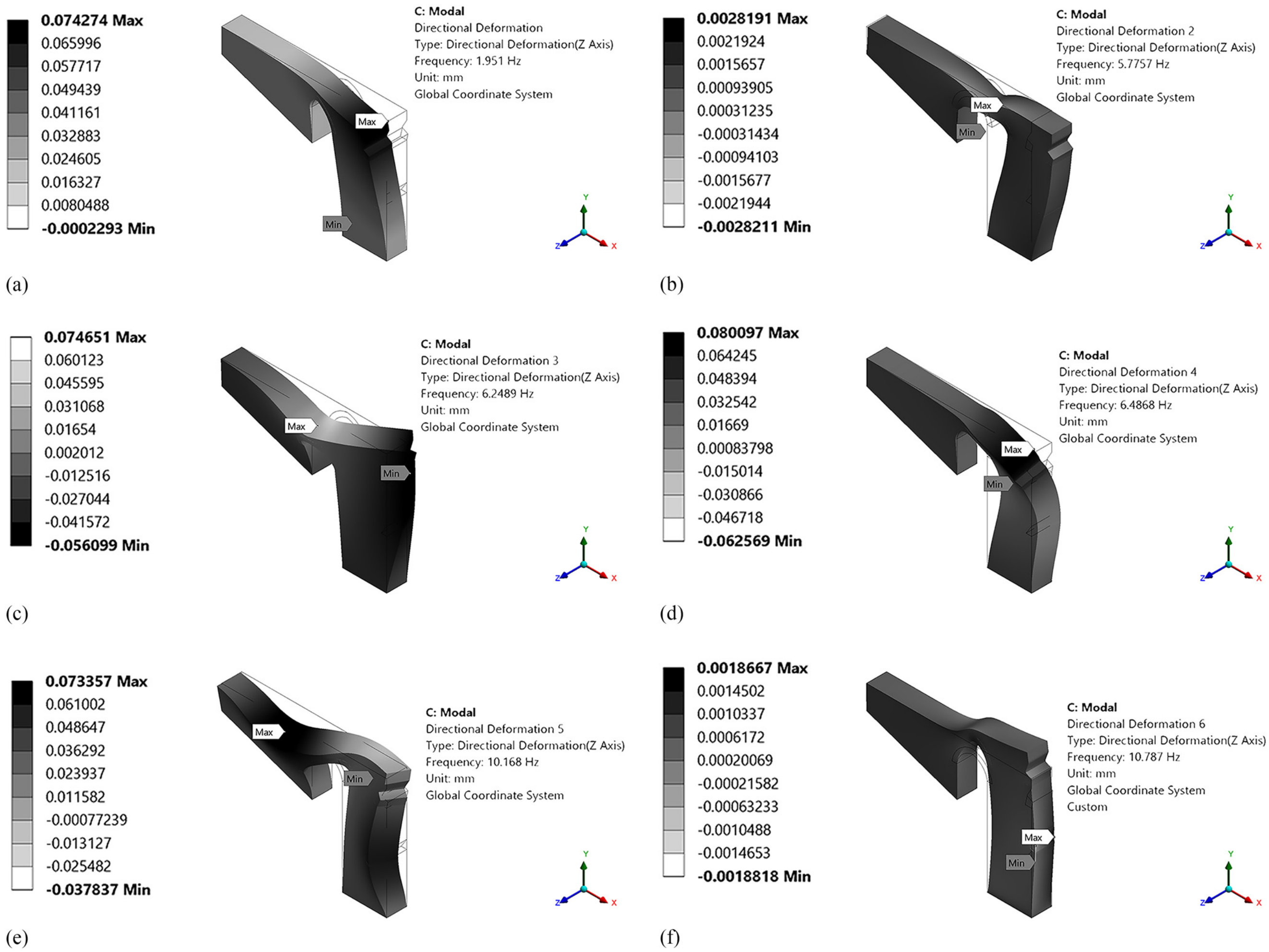

Fig. 15. Six mode shapes of Portion B: (a) directional deformation; (b) directional deformation 2; (c) directional deformation 3; (d) directional deformation 4; (e) directional deformation 5; and (f) directional deformation 6.

Eurocode CEN (2003) proposes an equation for the estimation of Young's modulus value of stone masonry walls. The equation depends on the multiples of the compressive strength of the masonry. The recommended value is 1,000 times the compressive strength, which results in 10,490 MPa for this study.

Vasconcelos (2005) conducted an experimental study on the mechanics of stone masonry. Experimental results of nondestructive material testing on granite stone material were reported. Vasconcelos (2005) conducted in-plane quasi-static cyclic tests on different types of stone masonry walls. Young's modulus values were reported between 2,300 and 2,500 MPa for the andesite stone masonry walls.

Literature survey resulted with a range of Young's modulus values for the andesite stone masonry stone walls. In this study, two sets of numerical analyses were conducted by using Young's modulus values of 870 and 1,500 MPa. These values were chosen from the similar studies conducted by Ercan and Nuhoğlu (2014) and Nohutçu et al. (2015). Other material properties were obtained from Ercan and Nuhoğlu (2014) that are available in Table 3.

Modal analysis results are listed in Tables 4 and 5. Related mode shapes are given in Figs. 14 and 15. According to Figs. 14 and 15, the vibration mode shapes of the structure can be identified as lateral displacements. Table 4 demonstrates two sets of results with changing stone masonry Young's modulus values of 1,500 and 870 MPa. Table 4 compares the frequency values with the calculated and measured values reported by Ercan and Nuhoğlu (2014). According to Table 4, analyses with 1,500 MPa resulted with a minimum 2.2% difference in the first mode and a maximum 11.2% difference in the fourth mode compared to the experimental results. This difference is related to the inaccuracies within the numerical model. Inaccuracies can be related to the uncertainties in the material properties and also possible differences in boundary conditions. The difference can be decreased with the help of structural monitoring, and the numerical model can be calibrated by using modal analysis results. On the other hand, tests with 870 MPa diverged around 30% from the experimental results. This range of results shows that the frequency of the masonry structure is sensitive to Young's modulus value.

Time–history analysis is a useful tool to predict the response of the structure under different seismic excitations. Seismic response of the structure using a realistic numerical model can evaluate the structure better in restoration projects and results in a more reliable intervention.

In this study, the Vezirağa Aqueduct numerical model is subjected to the north–south component of the ground motion recorded at a site in El Centro, California, during the Imperial Valley, California, earthquake (PEER 1940). The peak ground acceleration value is 0.319 g. The earthquake excitation was applied to the structure through the z-axis, where the first mode shape was observed.

Transient-structural analyses were carried out by the ANSYS 3D finite-element program. Only geometrical nonlinearity was considered in the analyses. Equilibrium iterations were carried out by using the Newton-Raphson method.

In this study, the time–history analysis results of Part A are discussed. Time histories of the displacements in the z-direction and the principal stresses are the outputs of the earthquake analyses. According to the analyses, maximum displacement is 206.8 mm observed at the 12th second [Fig. 16(a)]. This value is the total displacement. Maximum displacement relative to the ground is obtained as 86.6 mm. Fig. 15 shows the contour plot of displacements in the z-direction and the principal stresses. Maximum principal stress values are obtained as 8.47 MPa for compression and 0.59 MPa for tension under the aqueduct. It has been found out that the maximum principal stress results are lower than the stone material principal stress values of 10.49 MPa for compression and 1.05 MPa for tension [Fig. 16(b)]. Fig. 17 gives the time–history plot of the maximum displacements in the z-direction.

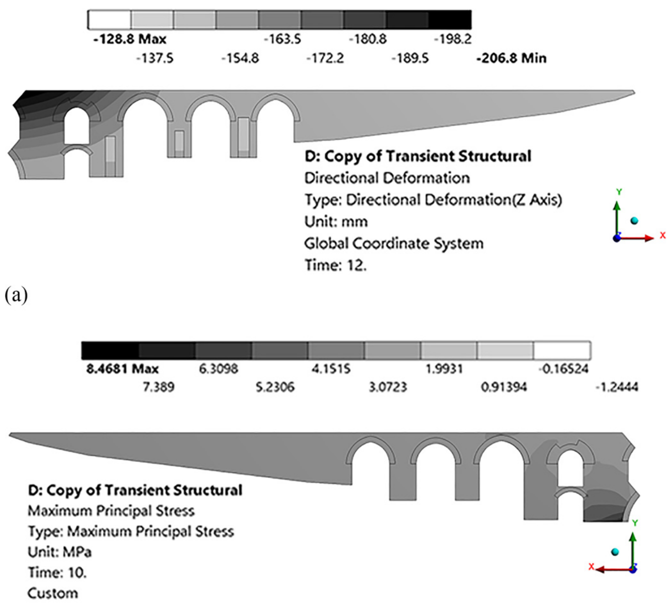

Fig. 16. Time–history analysis plots: (a) directional deformation (z-axis); and (b) maximum principal stress.

Comparative Study with Similar Examples

After the identification of physical characteristics, the comparative study with similar examples in Turkey from the sixteenth, seventeenth, and eighteenth centuries has been carried out to determine the historical value of the aqueduct. The parameters considered in the comparative study are period, location, form, characteristics of arches, construction techniques and materials, and conservation state (Figs. 18 and 19). Among the 11 aqueducts analyzed within the content of this study, 9 are in İstanbul and 2 in İzmir. Ten of these are linear in form, and the only L-shaped example is the Kırık Aqueduct. The shape is related to site characteristics. Eight of these aqueducts have depressed arches including Veziriağa, and three of them have semicircular arches. All of the İstanbul examples are constructed out of cut stone in both walls and arches, while the İzmir ones are out of rubble stone reinforced with reused cut stone in the walls and brick in the arches. Eight of the nine İstanbul examples have sustained their integrity, but both of the İzmir examples have partial losses and need comprehensive restoration. As is seen in Fig. 19, four of the aqueducts carry water from a brook or lake to another architectural monument. Three of them carry water to towns or cities. Three of eleven take water from an unknown source to a dam lake. Only one of them is in a water conveyance system with no information. The Veziriağa Aqueduct carried water from the Kozağaç brook to 10 old fountains and 73 new fountains in the İzmir city center in the seventeenth century.

Fig. 17. Time-displacement data at the ground and top for Portion A.

COMPARATIVE STUDY WITH SIMILAR EXAMPLES FROM OTTOMAN PERIOD (16th, 17th and 18th century)

Aqueduct Examples / Building Elements	Position	Dimensions (w x l x h m)	Form	Arch Series	Arch Profile	Double Arch	Buttresses	Stone Duct	Material
Veziraǧa Aqueduct 1674	Melez Valley İzmir	1.7x165x13	Linear	●	Depressed	●	●	●	Rubble Stone Brick
Avasköy Aqueduct 16th century	Atışalanı İstanbul	1.5x158.2x8.2	Linear	●	Depressed	-	●	●	Cut Stone
Güzelce Aqueduct 16th century	Alibey Brook İstanbul	2.6x155x29.5	Linear	●	Depressed	●	●	●	Cut Stone
Kırık Aqueduct 1554 - 1562	Kemerburgaz İstanbul	-x408x35	L Shaped	●	Semi-circular	●	●	●	Cut Stone
Maǧlova Aqueduct 1554 - 1562	Alibey Brook Valley İstanbul	-x257x36	Linear	●	Depressed	●	●	●	Cut Stone
Paşadere Aqueduct 1554 - 1564	Kemerburgaz İstanbul	-x102x-	Linear	●	Semi-circular	●	●	●	Cut Stone
Uzun Aqueduct 1554 - 1564	Kaǧıthane Brook İstanbul	-x710x26	Linear	●	Semi-circular	●	●	●	Cut Stone Rubble Stone
Osmanaǧa Aqueduct 18th century	Melez Valley İzmir	-x120x-	Linear	●	Depressed	●	●	●	Rubble Stone Brick
Büyükdere Aqueduct 1731	İstanbul	-	Linear	●	Depressed	-	●	-	-
Ayvat Aqueduct 1765	Ayvat Brook İstanbul	-x63x13.4	Linear	●	Depressed	-	●	-	Rubble Stone
Ali Paşa Aqueduct 1790 - 1791	Bayrampaşa İstanbul	-	Linear	●	Depressed	●	●	-	Cut Stone

Fig. 18. General characteristics of compared examples from the Ottoman Period (sixteenth, seventeenth, and eighteenth centuries).

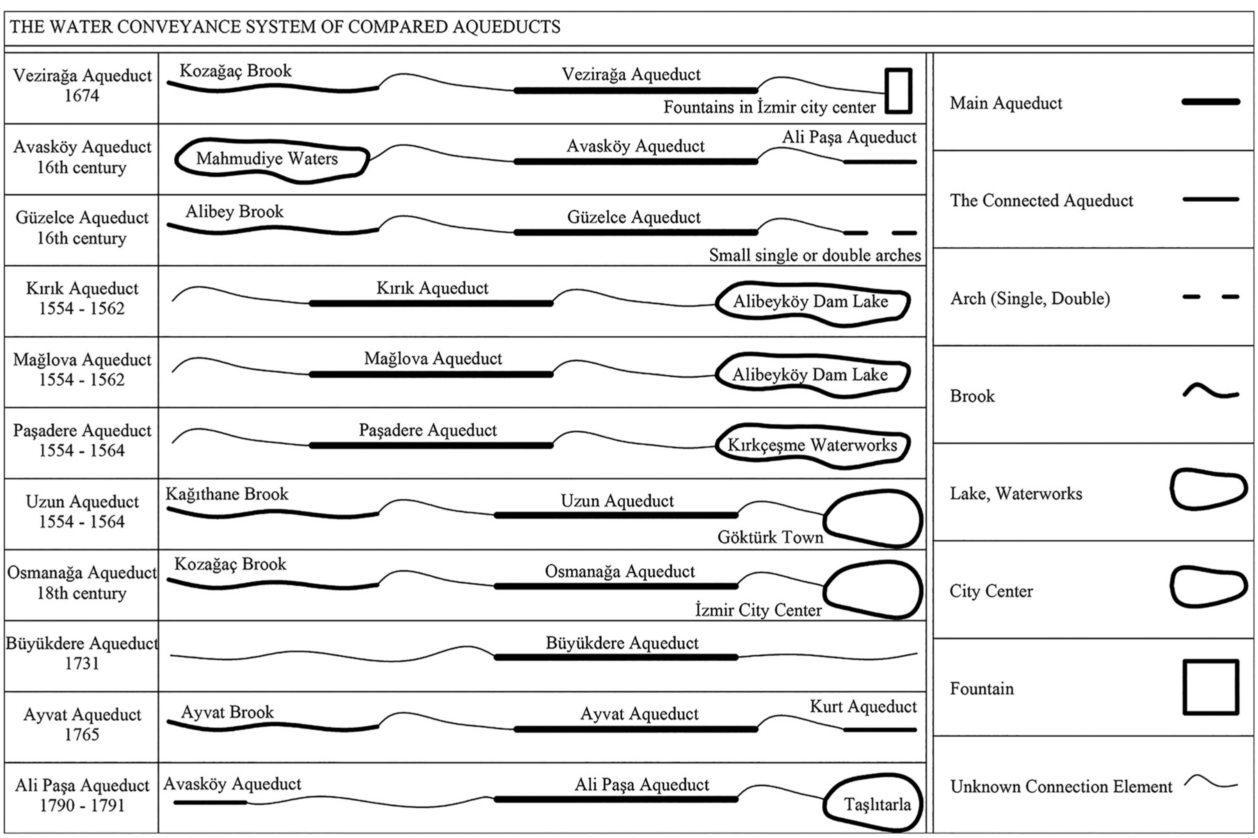

Fig. 19. Water conveyance systems of compared aqueducts.

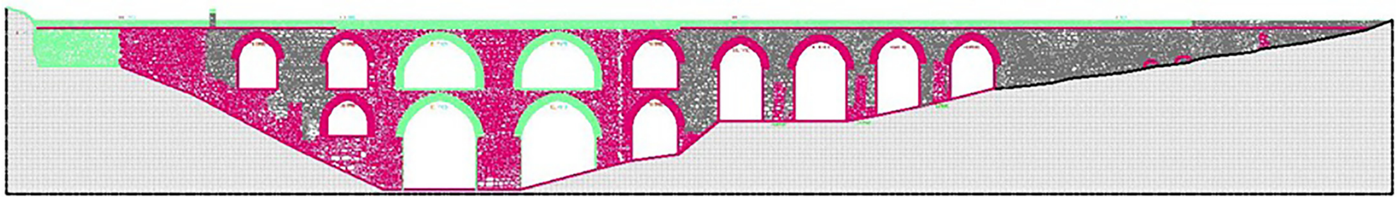

Fig. 20. Restitution, east elevation.

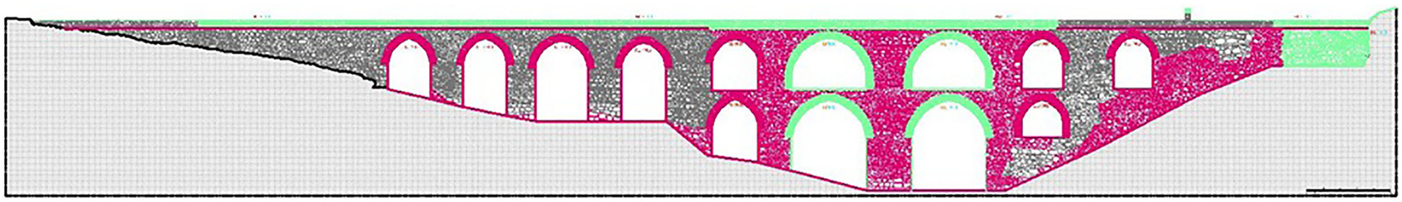

Fig. 21. Restitution, west elevation.

Periods and Restitution of the Vezirağa Aqueduct

The Vezirağa Aqueduct was faced with six periods during it life span. The first period, which was fourth-century BC, was the least reliable since it was only based on discussions of travelers. The second period was the construction of the Vezirağa Aqueduct by Köprülü Fazıl Ahmet Paşa (Ürer 2013). It was built in two stories composed of four arches at the bottom and nine arches at the top. The third period was the construction of the buttresses on the eastern facade. According to the site observations, historical research on earthquakes and Georg Weber's interpretations, these buttresses were added to the wall just after its construction. The exact date of the addition is not known. It may be claimed that it might be related to the 1688 earthquake. The fourth period was the addition of a supportive arch to the fourth arch from the northern end. Georg Weber stated that the aqueduct was repaired around the 1870s, and to solve the structural problems of the fourth arch, an additional arch was constructed under the original arch. Furthermore, in 1866, the İzmir-Aydın railway was constructed. The railway passed through the south end of the aqueduct. The demolishment between Portions B and C might have occurred on that date (Weber 2011). The fifth period was the demolishment of most of the arches. The arches in the center collapsed in a spate in 1931 (Akyüz Levi 2009). In the demolishment, the aqueduct lost four of its bottom arches and four of its top arches. The sixth period was the construction of the concrete duct and addition of the iron reinforcements to the southern end of 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 Portion A. However, the dates of these applications are not known exactly. The restitution for the original state of the Vezirağa Aqueduct in 1674 has been formulated at high reliability since there have been sufficient traces and old photographs (Figs. 20 and 21).

Evaluation and Conclusion

This study identifies the architectural and structural characteristics of the 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 seventeenth century and representing the value of water and water structures in the past. Sustaining its authenticity to a great amount, the aqueduct gives information about the construction techniques, material characteristics, and craftsmanship of the seventeenth century. Therefore, the aqueduct has authenticity, historical and documentary values. It also has aesthetic value with its contribution to the picturesque qualities of the landscape comprising the ancient Mount Kadifekale, the valley, the brook, and the historical railway. According to the results from analyses, the structure might survive from major earthquakes. In order to better understand and investigate the behavior of the structure, detailed investigations on foundation, effects of traffic, and effects of site characteristics should be studied. And an intervention decision should be made depending on whether or not strengthening of the walls would be required. With all these values and characteristics, the aqueduct must be protected as a historical landmark of İzmir. This study has provided a contribution to the cultural inventory of Turkey since the aqueduct, as a heritage type, has been considered in a limited amount.

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Notation

The following symbols are used in this paper:

$c_{(\max)}$ = maximum seismic coefficient;
$\delta_{(\max)}$ = deflection of the structure (cm);
$T_{(s-\mathrm{eff})}$ = natural period of the pier (s);
$a_{(0)}$ = overturning acceleration (g); and
$K_{(s-\mathrm{eff})}$ = effective secant stiffness (g).

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