Bitlis Eren Üniversitesi Fen Bilimleri Dergisi
BİTLİS EREN UNIVERSITY JOURNAL OF SCIENCE
ISSN: 2147-3129/e-ISSN: 2147-3188
VOLUME: 12 NO: 2 PAGE: 544-556 YEAR: 2023
DOI:10.17798/bitlisfen.1263557

Assessing Seismic Crack Performance of Diyarbakır Çüngüş Masonry Stone Bridge Considering 2023 Kahramanmaraş, Hatay, Malatya, Gaziantep Earthquakes

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Keywords: Earthquake, Masonry Stone Arch Bridge, Non-Reflecting Boundary Condition, 2023 Kahramanmaraş Earthquakes, Seismic Analysis.

Abstract

Examination of the creep behavior of historical structures and the correct assessment of seismic failures in historical structures are of great importance for the safety and future of these important structures. In this study, time-dependent settlement and three-dimensional (3D) seismic analyses of a historical stone bridge were investigated using the 3D discrete element modeling technique. For the settlement and seismic analyses, the historical single-span Çüngüş bridge which was built in the 18th century in Diyarbakır,Türkiye by Ottoman Empire was used. Since Diyarbakır is in a dangerous zone according to the Türkiye seismic map, the examination of this structure is very critical for the history of Türkiye. The 3D model of the bridge was created using the FLAC3D program based on the finite-difference method and all the stone elements in the historical bridge were modeled separately as blocks. Special interaction elements were defined between the discretely modeled stones. For settlement creep analyses, the Burger-creep material model, which was not used for the creep behavior of historical buildings in the past, was utilized. Firstly, the 500-year long-term creep behavior of the bridge was examined by considering the fix boundary condition and full reservoir condition. According to the creep analyses, it was seen that the most deformation and failure section of the bridge is the arch section. Then, for the seismic analyses of the bridge, free-field and quiet non-reflecting boundary conditions were defined in the model. Furthermore, hysteresis damping coefficients were taken into account in seismic analyses with the help of special FLAC3D code. 10 different earthquakes were considered for the seismic analyses. According to the earthquake analyses, the earthquake behavior of the Çüngüş historical bridge was assessed by considering the full reservoir condition and it was understood that the 2023 Kahramanmaraş, Hatay, Malatya, Gaziantep earthquakes significantly changed the seismic safety behavior of Çüngüş single-span historical bridge.

1. Introduction

Historical buildings can provide important information about the past of countries, and the preservation of these structures is of great importance for the history of countries. For these structures to serve humanity more, the time-dependent failure behavior of the stone elements should be examined and restored. In addition, examining the earthquake behavior of historical buildings in seismic regions and taking precautions is very critical for the safety of these structures. Bridges are one of the most important examples of historical structures built in the past. There are many studies on the seismic analyses of historical bridges in the literature. Aydin and Özkaya [1] performed the structural analyses of the Sarpdere historical stone bridge. Firstly, a three-dimensional finite element model of the bridge was

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Received:11.03.2023, Accepted:25.05.2023

generated by using ANSYS software. The total maximum load-carrying capacity behavior of the bridge was evaluated and it was seen from numerical analyses that the maximum cracks occurred on the arch section of the bridge. The location of the arch section of a masonry bridge can vary depending on the specific design and construction of the bridge. However, typically, the arch section is located in the middle or center of the bridge span, as this is where the greatest weight and pressure from the weight of the bridge and any vehicles or loads crossing it are concentrated. The arch section is designed to distribute this weight and pressure evenly across the entire span of the bridge, providing support and stability to the structure. Bayraktar and Hokelekli [2] assessed the structural behavior of brick and stone historical bridges considering nonlinear soil deformability effects. Bridges were modeled as three-dimensional using brick and wedge elements. According to seismic analyses, it was seen that the most critical section of the bridge during an earthquake is the arch section. Furthermore, the seismic behaviors of the brick and stone bridges are very different from each other. Bergamo et al. [3] investigated the stress and deformed behavior of historical stone bridges. Firstly, the mechanical properties of the bridge were acquired from experimental tests. Then, static experimental tests were performed to obtain the static behavior of the bridge. The three-dimensional finite element model of the bridge was created and maximum deformations occurred on the arch section of the bridge. Conde et al. [4] evaluated the influences of material properties and geometry of the arch section of the bridge on the structural behavior of the Monforte de Lemos historical stone bridge. According to four different arch types, it was seen that arch types have enormous effects on the structural behavior of bridges. Moreover, arch types have significant static effects on the collapse behavior of bridges. Conde et al. [5] investigated the probabilistic analyses of the stone arch bridges using the finite element model and limit analysis model. According to numerical analyses, the maximum failure damages occurred on the arch section of the bridge. Moreover, very different reliability indexes were observed for EN 1990, ISO 2394, ISO 13822, JCSS, and fib standards. Gönen and Soyöz [6] examined the three-dimensional earthquake behavior of the historical stone bridges using the finite element macro-modeling approach. The bridge was modeled as three-dimensional using ANSYS software and nonlinear earthquake analyses were performed under 14 various strong ground motions. It was proposed that future studies should aim at determining the performance criteria for historical stone bridges. Güllü and Jaf [7] evaluated the three-dimensional earthquake behavior of the Mataracı historical stone bridge. After the three-dimensional model of the bridge was created, 5 different modes of the bridge were examined by considering the soil-structure interaction and fix base. Besides, the seismic behavior of the bridge was evaluated considering a strong earthquake. According to seismic analyses, it has been understood that modeling historical bridges by considering the soil-structure interaction and fix base significantly changes the seismic behavior of these structures. Naderi and Zekavati [8] evaluated the earthquake behavior of historical stone bridges using the finite element method and discrete element method. The first five modes of the bridge were assessed in detail and it was seen that the first mode of the bridge is 4.985 Hz. Then, the seismic deformation behavior of the bridge was evaluated and it was understood that the maximum deformations occurred on the arch section of the bridge during the earthquakes. Rovithis and Pitilakis [9] examined the static behavior of a historical stone bridge. The three-dimensional model of the bridge was created considering the fixed-base model, the flexible-base model, and the flexible-base rehabilitated model. According to these models, the frequency for Mode 1 is 11.27 Hz, 1.62 Hz, and 2.058 Hz for the fixed-base model, the flexible-base model, and the flexible-base rehabilitated model, respectively. Moreover, the response spectrum behavior of the bridge was assessed considering the free-field ground response analyses. Saygılı and Lemos [10] evaluated the earthquake damage performance of the masonry bridges. Historical Kazan and Şenyuva bridges were utilized for the numerical analyses. Firstly, three-dimensional models of the bridges were created using SAP2000 and 3DEC software, and the first five modes of the bridges were assessed in detail. According to numerical analyses, it was seen that the maximum relative X displacements during the earthquake occurred on Point 5, and the maximum relative traversal displacements were observed on Point 4. Sayin [11] assessed the nonlinear earthquake behavior of the historical Nadir Bridge. The bridge was modeled as three-dimensional and it was understood that strong ground motions strongly affect the seismic behavior of historical bridges. Simos et al. [12] investigated the effects of near-fault and far-fault earthquakes on the seismic behavior of the Konitsa historical stone bridges. Surface contact was defined in the model. Firstly, a three-dimensional finite element model of the bridge was created and seismic analyses were performed considering a near-fault and a far-fault earthquake. 5 Modes of the bridge were evaluated and it was seen that the first mode of the bridge is 2.3136 Hz. Then, the crack behavior of the bridge was assessed in detail and it was understood that maximum cracks occurred on the arch of the bridge. Zani et al. [13] examined the effects of soil compressibility on the structural behavior of historical stone bridges. Firstly, the structural behavior of the bridge was checked using load tests and the Italian Technical Regulations. Then, the bridge was modeled as three-dimensional and the deformation behavior of the bridge was assessed in detail. According to three various models of the bridge, it was seen that the maximum principal stress is 3.1x105 MPa for Model A. Karalar and Çavuşli [14] examined the structural performance of a historical building considering 2018 TBEC. Furthermore, there are many studies about static and seismic analyses of historical stone bridges in the literature [15-16], [22-26]. It was seen from these studies that the Burger-creep material model, free-field non-reflecting boundary condition, quiet non-reflecting boundary condition, three-dimensional discrete modeling, and special interaction parameters (kn and ks) were not used to perform the creep and seismic analyses of the historical stone arch bridges in the past studies. For this reason, this study is very important to fill these deficiencies in the literature. In this study, the creep and seismic behaviors of the Çüngüş historical stone arch bridge built in the 18th century in Diyarbakır, Türkiye were investigated in detail. Firstly, the three-dimensional creep model and the three-dimensional seismic model of the bridge were created. While creating the three-dimensional creep model, each stone element in the arch section of the bridge was modeled separately. This modeling process was done with the help of FLAC3D code based on the finite-difference method. This method is a numerical technique for solving differential equations by approximating derivatives with finite differences and it converts differential equations, which may be nonlinear, into a system of linear equations that can be solved by matrix algebra techniques. Special interaction parameters (k_n and k_s) were defined between the stone elements modeled separately. When the literature is examined, it is seen that there are very limited studies in which the creep and seismic analyzes of historical stone bridges are examined by modeling discrete stone elements and by assigning special k_n and k_s interaction elements between each stone element. Therefore, the first aim of this study is to examine how discrete element modeling and specific interaction elements change the creep settlement and seismic behavior of historical bridges. The Burger-Creep material model, which was not used in the past to examine the creep settlement behavior of historical bridges, was used in the creep settlement analyses. The Burgers-Creep material model is a visco-plastic model combining the Burgers model and the Mohr-Coulomb model [18]. The second aim of this study is to fill this gap in the literature and observe how the Burger-Creep material model changes the long-term creep behavior of historical bridges. Then, special free-field and quiet boundary conditions were utilized for the seismic analyses of the bridge. The other purpose of this study is to examine the effects of free-field and quiet boundary conditions on the seismic behavior of historical arch-stone bridges. A total of 10 different near-fault earthquakes were used in seismic analyses, and one of the most important purposes of this study is to reveal the effects of near-fault earthquakes on the seismic behavior of historical stone bridges. This study is of great importance in terms of eliminating the deficiencies in the literature.

INDEX OF ABBREVIATIONS	
M_w	*Moment Magnitude*
PGA	*Peak Ground Acceleration*
PGV	*Peak Ground Velocity*
PGD	*Peak Ground Displacement*
k_n	*Normal Stiffness*
k_s	*Shear Stiffness*
E	*Modulus of Elasticity*
f_c	*Compressive Strength*
μ	*Poisson's Ratio*

2. Çüngüş Historical Arch Bridge and Seismic Hazard Map of Diyarbakır-Türkiye

Diyarbakır Çüngüş stone bridge is one of the most important historical structures in Türkiye (Fig. 1). In the literature, there is no information about its period and builder. However, it is estimated that the bridge was built in the 18th (1743) century in terms of plan and architecture. The main construction material of the bridge, which has one span and a pointed arch, is yellow limestone obtained from the region. The arch thickness is 0.53 m and the spandrel wall thickness is 0.41 m. The feet of the bridge are set on natural rocks. The bridge has 34.74 m long, 5 m wide, and 16.42 m high. The span of the arch is 9.32 m at the ends where the feet sit on the rocks. The tissue, which deteriorated over time, was not repaired with the same technique but was replaced with rubble material that requires less labor. The upper section of the bridge was also recently covered with interlocking cobblestone. Signs of different periods have been detected on the upstream surface. Besides, stone remains were found about 10 m away from the upstream face of the bridge.

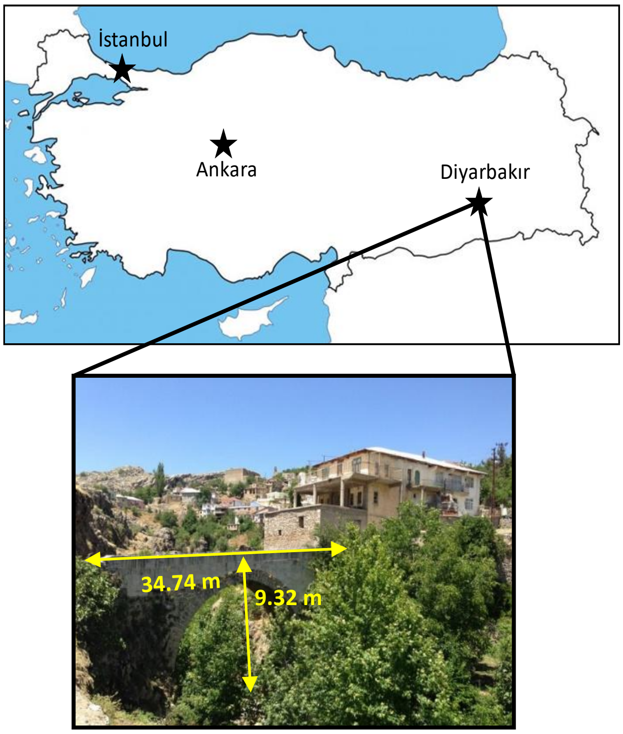

Figure 1. General view of the Çüngüş stone arch bridge.

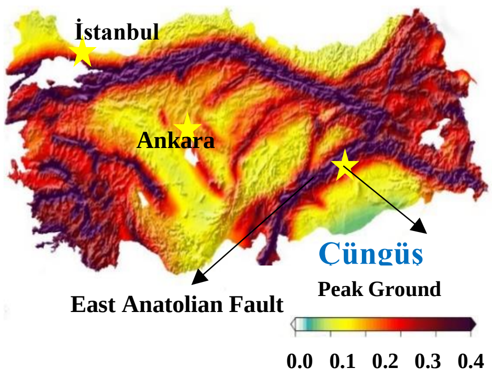

Figure 2. The fault map of Türkiye [17].

Çüngüş stone arch bridge is a historical building built on seismic active earthquake zones in Diyarbakır, Türkiye. This bridge is located on the East Anatolian Fault and this fault is in constant motion. Türkiye's seismic map was shown in detail in Fig. 2. According to Fig. 2, it was seen that the Çüngüş bridge has been exposed to many important earthquakes from the past to the present, and examining the seismic behavior of this structure is of great importance for the future of this structure. As a result of the earthquakes that took place in Diyarbakir in the past, it was determined that there was no structural damage to the Cungus bridge. However, due to time, significant abrasions were observed on the stone elements of the bridge. Besides, according to the observation results, visible displacements and seismic failures occurred in the body and arch parts of the bridge as a result of the 2023 Kahramanmaraş earthquake. The region where the Cüngüş bridge is located was exposed to major earthquakes in 2023. The East Anatolian Fault (EAF) produced very large earthquakes in the Kahramanmaraş, Hatay, Malatya, and Gaziantep in 2023 and as a result of these earthquakes, great destructions occurred. Besides, these earthquakes have caused the death of thousands of people in these provinces. It is of vital importance to examine these current and severe earthquakes and to model our structures according to these earthquakes. In this study, the earthquake behavior of the Cüngüş bridge, which is located on the EAF, was investigated by considering the 2023 Kahramanmaraş, Hatay, Malatya, and Gaziantep earthquakes. The characteristics of the earthquakes used in seismic analyses were summarized in Table 1 in detail.

Table 1. Characteristic properties of strong ground motions [19].

Case	Earthquake	Year	M_w	Distance (km)	PGA (cm/s²)	PGV (cm/s)
1	Pazarcık1 (K.maraş)		7.7	8.6	2178.71 (E-W)	186.78 (E-W)
2	Elbistan (K.maraş)		7.6	7	635.45 (N-S)	170.79 (N-S)
3	Nurdağı1 (Gaziantep)		6.6	6.2	454.15 (N-S)	44.60 (U-D)
4	Yayladağı (Hatay)		6.4	21.7	775.40 (N-S)	75.79 (E-W)
5	İslahiye (Gaziantep)		5.7	11.19	363.52 (E-W)	13.85 (E-W)
6	Yeşilyurt (Malatya)	2023	5.6	6.15	25.23 (E-W)	2.36 (N-S)
7	Doğanşehir (Malatya)		5.6	10.23	47.28 (E-W)	2.90 (E-W)
8	Nurdağı2 (Gaziantep)		5.6	6.98	44.15 (E-W)	2.91 (E-W)
9	Pazarcık2 (K.maraş)		5.5	5.96	49.84 (U-D)	2.84 (N-S)
10	Ekinözü (K.maraş)		5.5	10.93	79.35 (E-W)	4.26 (E-W)

3. Three-Dimensional Finite Difference Model of Bridge

In this study, it was aimed to examine the creep and seismic behaviors of the historical Çüngüş stone bridge built in the 18th century in Diyarbakır, Türkiye. For this purpose, the three-dimensional model of the bridge was modeled with the help of the FLAC3D program. The discrete element method was used for modeling the bridge. Firstly, the arch of the bridge was formed. Then, each stone element in the arch part was modeled separately and interaction stiffness coefficients were defined between the interface surfaces of the stone elements by considering the kn and ks coefficients [18]. A total of 2672 stone elements were used in the arch part of the bridge. In addition, a total of 94883 and 297529 stone elements were utilized in the rockfill and foundation of the bridge, respectively. In the FLAC3D program, "kn" and "ks" are stiffness interface parameters that are used to define the behavior of the material constitutive model for the simulation of geological and geotechnical processes. "kn" refers to the normal stiffness interface parameter, which represents the resistance to compression and extension of the material. It determines the response of the material to normal stresses or strains, perpendicular to the surface. Then, "ks" refers to the shear stiffness interface parameter, which represents the resistance to shearing of the material. It determines the response of the material to shear stresses or strains, parallel to the surface. In FLAC3D, these parameters are often used in the definition of contact models between different materials or between the material and the boundaries or the loads in the simulation. Then, rockfill elements were separately modeled on the arch, and all rockfill elements built on the arch were defined to the program with the help of special FLAC3D codes. All dimensions of the stones were modeled following the survey project of the bridge (Fig. 3).

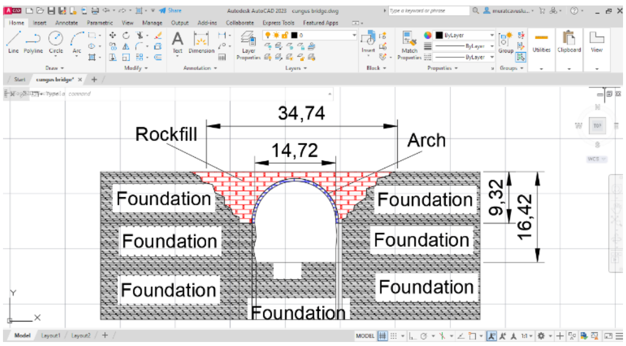

Figure 3. Survey AutoCAD project of Çüngüş bridge.

Finally, the foundation section of the bridge was created. While creating the foundation section of the bridge, it was extended to the sides as the height of the arch. For the upstream and downstream sections of the bridge, it was extended as three times the height of the arch [20-21]. Furthermore, the foundation section was extended towards the underside of the arch as five times the height of the arch. After the three-dimensional model of the bridge was created, the fix (reflecting) boundary condition was defined in the z-direction at the base of the bridge for creep settlement analyses. On the lateral parts of the bridge, the fix boundary condition was defined in the x and y directions. Besides, for seismic analyses, quiet (non-reflecting) boundary condition was defined at the base of the model. The free-field boundary condition was taken into account for the lateral parts of the model. These non-reflective boundary conditions ensure that seismic waves are not reflected in the model and provide realistic analyses for seismic analyses [20-21]. The Burger-creep material model was taken into account for creep analyses. The burger-creep material model is one of the important material models derived to examine the failure behavior of elements such as stones, and this model has not been used to examine the creep settlement behavior of historic bridges in the past [18]. The Burger creep model is a viscoelastic-plastic model used to simulate the deformation behavior of rocks and soils under sustained loading conditions. It is based on power-law rheology, which describes the deformation rate as a function of stress and temperature. The model takes into account three components of deformation: elastic, viscoelastic, and plastic. The elastic component is characterized by the linear relationship between stress and strain, while the viscoelastic component is characterized by the power-law relationship between stress and time-dependent strain rate. The plastic component is characterized by the power-law relationship between stress and strain. While performing the long-term creep analyses, time intervals were defined using special fish codes. Moreover, special hysteresis damping elements were defined for seismic analyses. The three-dimensional finite-difference model of the bridge was shown in Fig. 4. Moreover, the material properties of the Çüngüş bridge were summarized in Table 2.

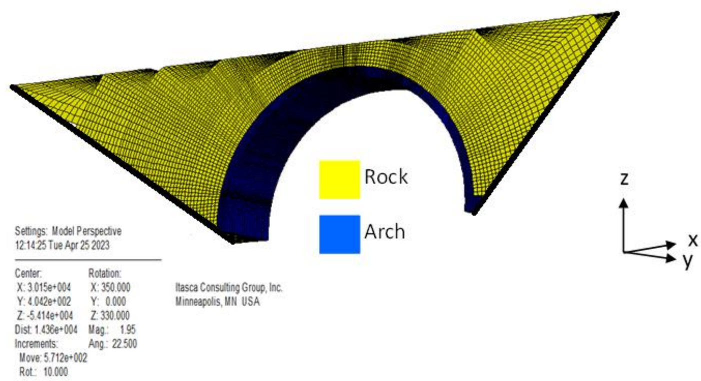

Figure 4. Three-dimensional finite-difference model of the Çüngüş bridge.

Table 2. Summary of the material properties of the Çüngüş bridge [20-21].

Material Property	Arch	Rockfill Material	Foundation
E	8.8 (GPa)	8.1 (GPa)	9.8 (GPa)
fc	7.7 (MPa)	6.9 (MPa)	10.1 (MPa)
μ	0.28	0.25	0.36

4. Three-Dimensional Creep and Seismic Analysis Results

In this section, time-dependent creep settlement and nonlinear seismic analysis results of the historical Çüngüş arch bridge were shown in detail. The Burger-Creep material model, which was not previously used for time-dependent creep analysis of historical arch bridges in the past, was utilized in the creep and failure analyses. Creep settlement analyses were performed for the 500-year failure behavior of the Çüngüş bridge. In Fig. 5, the first five modes of the bridge obtained as a result of creep analyses were presented in detail. According to Fig. 5, the first mode is 1.89 Hz and this value allows us to gain significant information about the modal behavior of the historical bridges. Moreover, the second mode of the bridge is 3.34 Hz. As a result of the modal analyses, the 3rd mode, the 4th mode, and 5th mode of the Çüngüş bridge are 3.98 Hz, 4.31 Hz, and 4.85 Hz, respectively (Fig. 5). These values are of great importance for observing the modal behaviors of historical bridges. Besides, the 5 different modes of the bridge obtained using the Burger-creep material model provide researchers with important information about how this material model affects the modal behavior of historical bridges (Fig. 5). In Fig. 6, the 500-year creep settlement behavior of the Çüngüş bridge was shown in detail. As Fig. 6 was investigated in detail, it was seen that the changing rate in the settlement behavior of the Çüngüş bridge increased continuously from 1973 to 2173. However, after a certain time, the changing rate in the failure behavior of the bridge decreased. As Fig. 6 was assessed in detail, between 1773 and 1873, no large displacement changes were observed in the bridge body. However, significant displacement increases occurred in the arch section of the bridge after 1973. From 1973 to 2173, about 5 mm of settlement took place in the middle section of the bridge. This result shows how much displacement increase will occur in the body of the Cüngüş bridge in the future. Between 2173 and 2273, significant displacement increases were not observed in the bridge body. As of 2173, settlement values in the bridge body will become stable. These results will guide researchers to estimate the displacement values that will occur in the future in the bodies of historical bridges (Fig. 6).

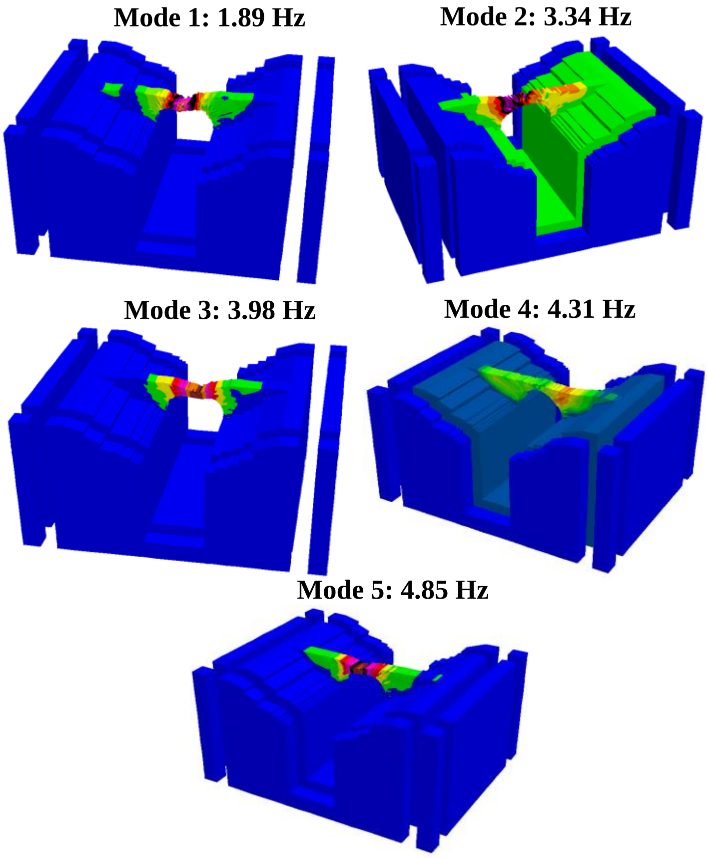

Figure 5. Modal analysis results of the Çüngüş bridge.

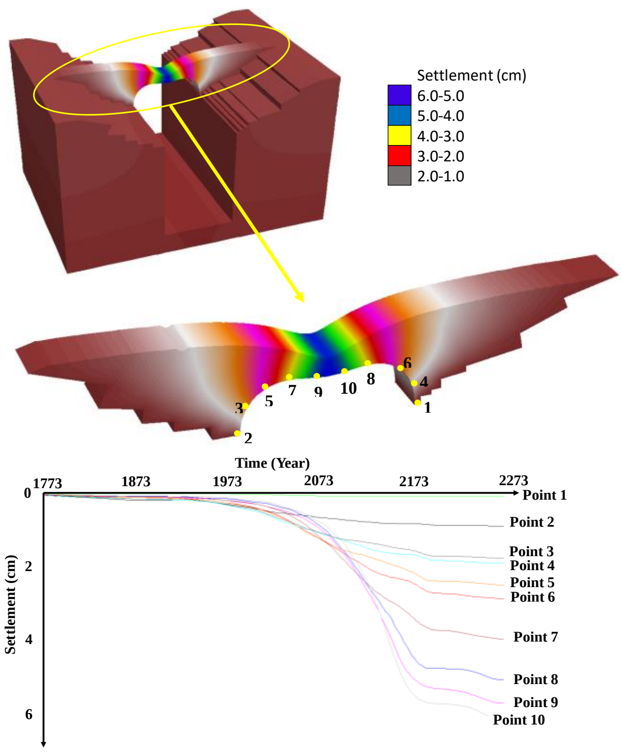

Figure 6. Long-term creep settlement analysis results of the Çüngüş bridge.

Furthermore, during 500 years, the largest displacements occurred on Point 9 and Point 10. Moreover, it was understood that the smallest displacements took place on Point 1 and Point 2. In Figs. 7-16, the seismic analysis results performed by considering the creep analysis results of the bridge were presented in detail. Earthquake accelerations were applied to the 3D model of the bridge in x, y, and z directions and seismic cracks that took place in the arch section of the bridge were also shown in detail. The seismic displacement results from the bridge are shown only for the vertical direction. In Fig. 7, the nonlinear earthquake analysis results of the bridge were shown for Case 1 (Pazarcık1 earthquake). For Case 1, it was seen that the greatest vertical displacements in the bridge occurred in the arch section of the bridge. However, significant displacements were not observed in the foundation section of the bridge (Fig. 7a). As the cracks that occurred in the arch and rockfill material parts of the bridge were examined in detail, it was understood that maximum cracks were observed in the middle parts of the arch section (Fig. 7b). Furthermore, it was seen that the maximum vertical displacements were obtained in the middle parts of the arch section, and the greatest displacement value in the middle parts of the arch section is 25,604 mm (Fig. 7c). As Fig. 8 was evaluated in detail, it was understood that the most critical section of the bridge is the arch section. Besides, for Case 2 (Elbistan earthquake) it was seen that the greatest displacement value in the arch section of the bridge is 24.382 mm. Moreover, significant deformations were observed in the arch section of the bridge for Case 2 (Fig. 8a). Fig. 8b shows the seismic cracks in the rockfill material section of the bridge. The largest cracks on the bridge were observed at the middle sections of the arch (Fig. 8b). In Fig. 9, the seismic analysis results of the bridge were shown for Case 3 (Nurdağı1 earthquake). According to Fig. 9a, it was concluded that the largest displacements (23.30 mm) on the bridge took place in the middle parts of the bridge. In addition, it was seen that the lowest displacements occurred in the feet sections of the bridge (Fig. 9a). In Fig. 9c, it was observed that the maximum displacements for Case 3 occurred in the middle parts of the arch section of the bridge. In Fig. 10, the earthquake behavior of the Çüngüş bridge was shown for Case 4 (Yayladağı earthquake) in detail. For Case 4, it was seen that the largest displacements took place in the arch part of the bridge. Moreover, it was understood that the smallest displacements took place in the foundation section of the bridge. 20.103 mm maximum displacement was observed in the middle of the arch section of the bridge. Approximately 4 mm maximum displacements were observed at the feet of the arch section (Fig. 10a). Besides, it was observed that significant cracks occurred in the middle of the arch part. These cracks may threaten the seismic safety of the bridge during the earthquake. For this reason, it was suggested that the earthquake safety of historical bridges should be interpreted by considering these seismic cracks (Fig. 10b). In Fig. 11, the earthquake analysis results of the Çüngüş bridge were presented for Case 5 (İslahiye earthquake). According to Case 5, the greatest displacement value in the arch part of the bridge is 19.067 mm (Fig. 11a). Moreover, it was seen that significant cracks occurred in the arch part of the bridge. It was observed that significant vertical bending took place in the arch section of the bridge during the earthquake (Fig. 11c).

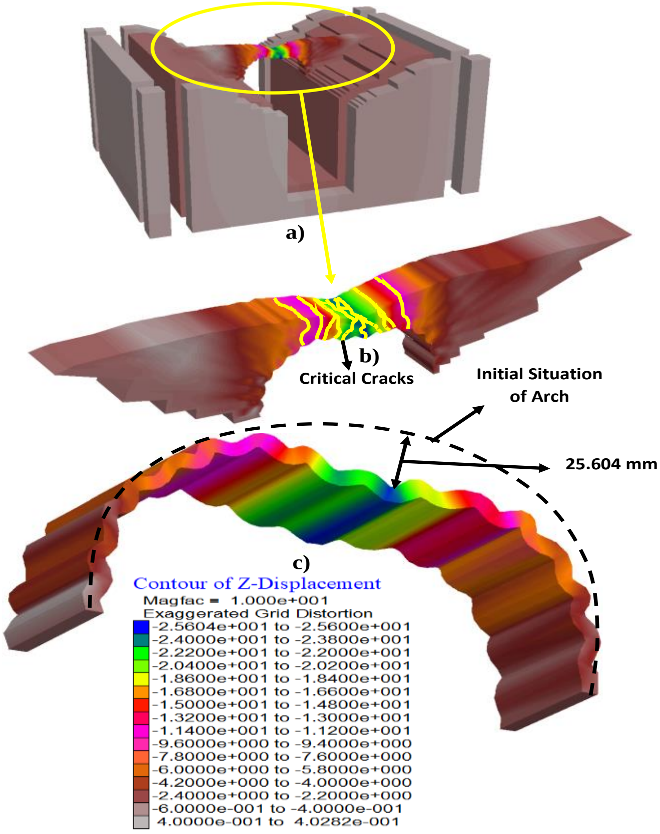

Figure 7. Seismic analysis results (mm) of the Çüngüş bridge for Case 1 (Pazarcık1 earthquake).

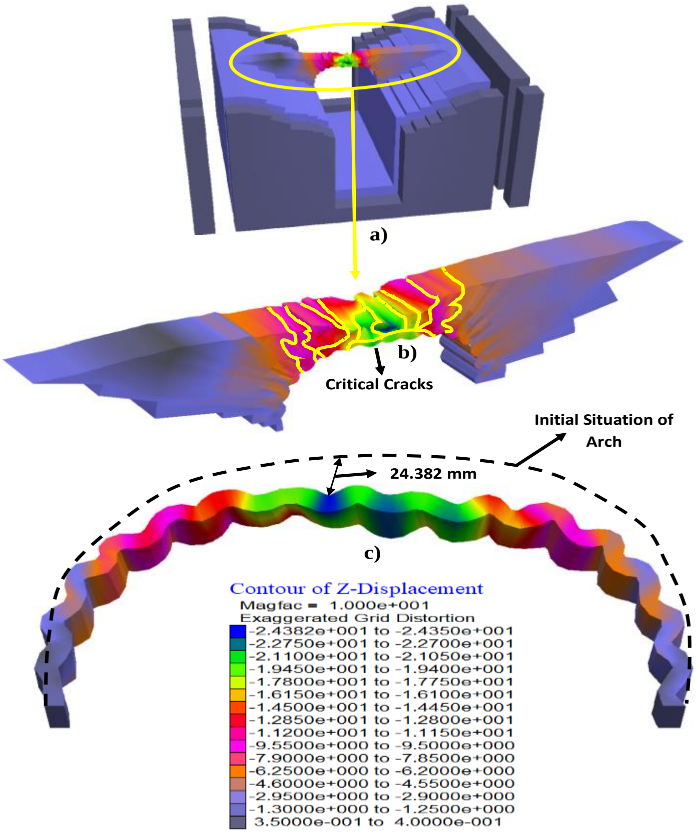

Figure 8. Seismic analysis results (mm) of the Çüngüş bridge for Case 2 (Elbistan earthquake).

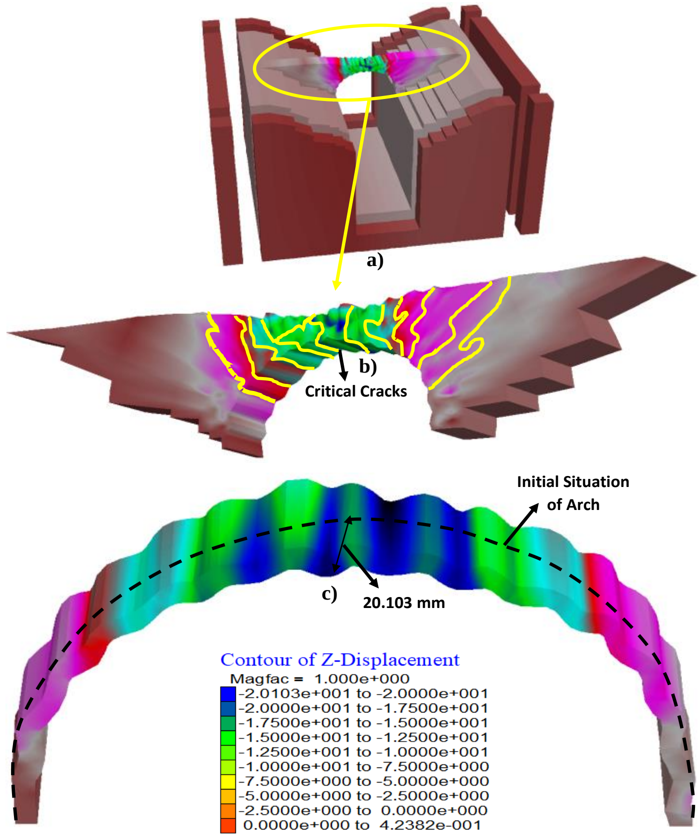

Figure 10. Seismic analysis results (mm) of the Çüngüş bridge for Case 4 (Yayladağı earthquake).

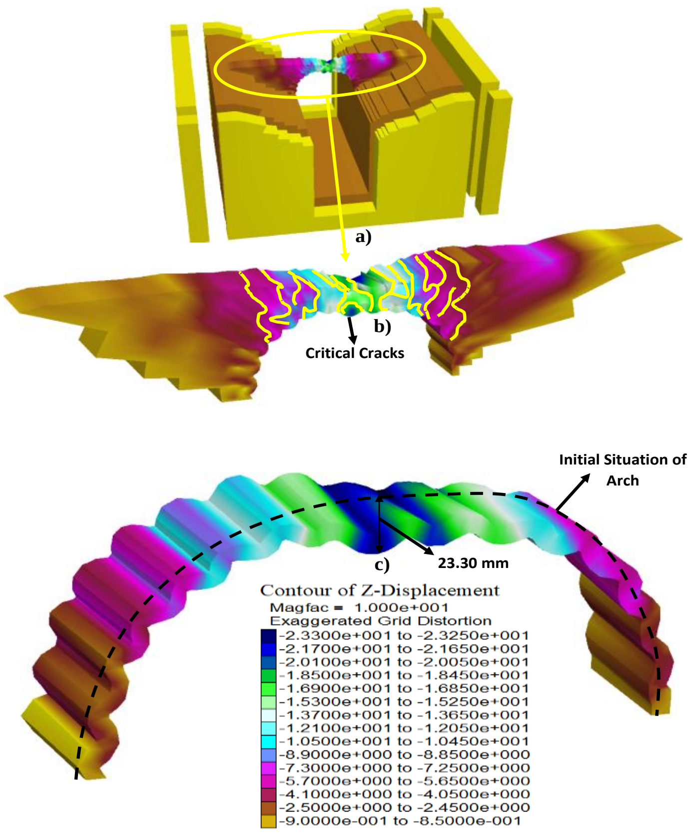

Figure 9. Seismic analysis results (mm) of the Çüngüş bridge for Case 3 (Nurdağı1 earthquake).

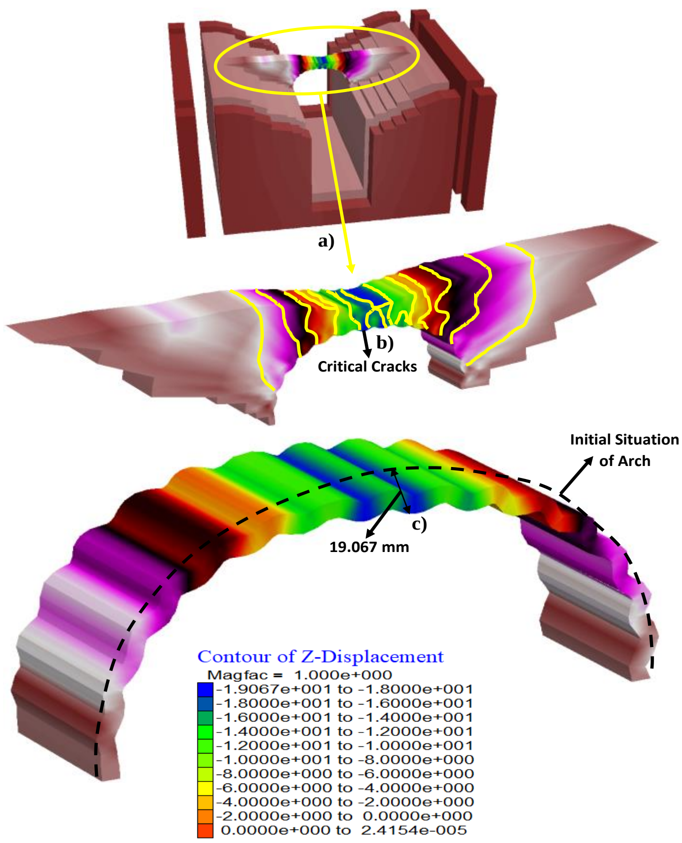

Figure 11. Seismic analysis results (mm) of the Çüngüş bridge for Case 5 (İslahiye earthquake).

In Fig. 12, the earthquake analysis of the Çüngüş arch stone bridge was examined for Case 6 (Yeşilyurt earthquake). As Fig. 12 was evaluated, it was understood that the vertical displacements and cracks in the arch section of the bridge are at serious levels. According to Fig. 12a, it was seen that the maximum vertical displacement value on the Çüngüş bridge is 16.07 mm. This maximum displacement value occurred at the edges of the arch section. Furthermore, it was understood that the smallest displacements observed in the bridge during the earthquake took place in the foundation. When Fig. 12b was assessed in detail, it was seen that the most critical cracks observed in the bridge during the earthquake occurred at the edges of the arch section. In Fig. 12c, only the seismic behavior of the arch section was investigated and it was seen that serious bending was acquired at the edges of the arch section. In Fig. 13, the nonlinear earthquake results and crack analysis results of the Çüngüş bridge were presented for Case 7 (Doğanşehir earthquake). For Case 7, it was seen that the most critical section of the bridge during the earthquake is the arch section. It was observed that the greatest vertical displacements took place in the middle sections of the Çüngüş bridge. It was understood that the greatest seismic vertical displacement value in the arch part is 14.322 mm (Fig. 13a). In Fig. 13b, it was concluded that the cracks that took place in the middle sections of the bridge are larger than the other parts of the bridge. In Fig. 13c, only the seismic behavior of the arch part was assessed and it was seen that the bending in the middle parts of the arch section is much larger than the other sections. From this result, it was understood that the most critical section of the Çüngüş bridge during the Doğanşehir earthquake is the middle parts of the arch section. In Fig. 14, the nonlinear seismic and crack behaviors of the Çüngüş bridge were evaluated for Case 8 (Nurdağı2 earthquake) in detail. According to Fig. 14, it was seen that the largest displacement value on the bridge is 13.04 mm. This value is very important for the seismic safety of historical bridges. Because even very small displacements on historical bridges can cause damage to these important structures. For this reason, it is strongly recommended to use the maximum seismic displacements obtained in this study for the restoration of historical arch bridges. In Fig. 15, the seismic analysis results of the historical Çüngüş bridge were presented for Case 9 (Pazarcık2 earthquake). According to Fig. 15, it was seen that the largest displacement value that took place in the Çüngüş bridge is 12.056 mm. It was observed that this numerical value occurred in the middle sections of the historical bridge. Fig. 15b shows the seismic cracks on the bridge for Case 9, and it was seen that the most critical cracks that occurred in the bridge during the earthquake took place in the middle sections of the bridge. Moreover, there are no significant seismic cracks in the edge parts of the bridge when compared to the middle sections of the bridge. In Fig. 15c, the seismic behavior of the arch section of the Çüngüş bridge was investigated and it was observed that serious bending took place in the middle parts of the arch section. In Fig. 16, the seismic analysis results of the Çüngüş bridge were presented for Case 10 (Ekinözü earthquake). According to Fig. 16a, the greatest vertical displacement value that occurred in the middle parts of the bridge during the earthquake is 8.849 mm. Smaller vertical displacements were acquired at the feet of the bridge (Fig. 16b).

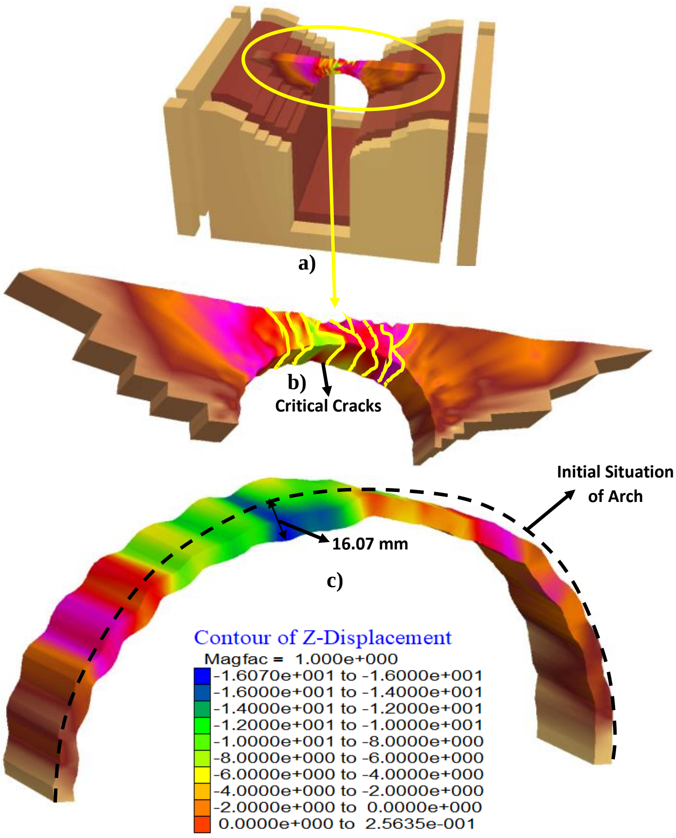

Figure 12. Seismic analysis results (mm) of the Çüngüş bridge for Case 6 (Yeşilyurt earthquake).

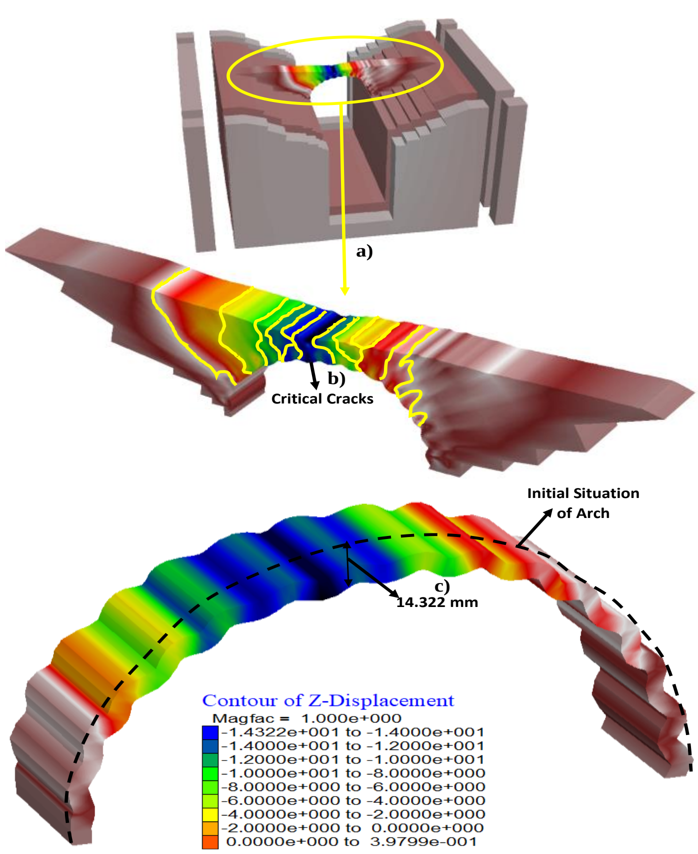

Figure 13. Seismic analysis results (mm) of the Çüngüş bridge for Case 7 (Doğanşehir earthquake).

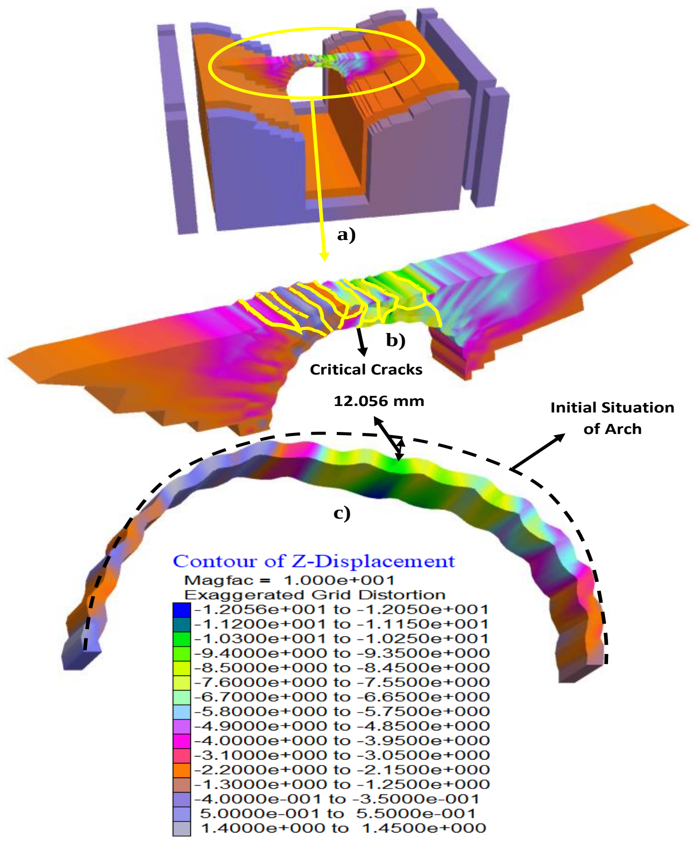

Figure 15. Seismic analysis results (mm) of the Çüngüş bridge for Case 9 (Pazarcık2 earthquake).

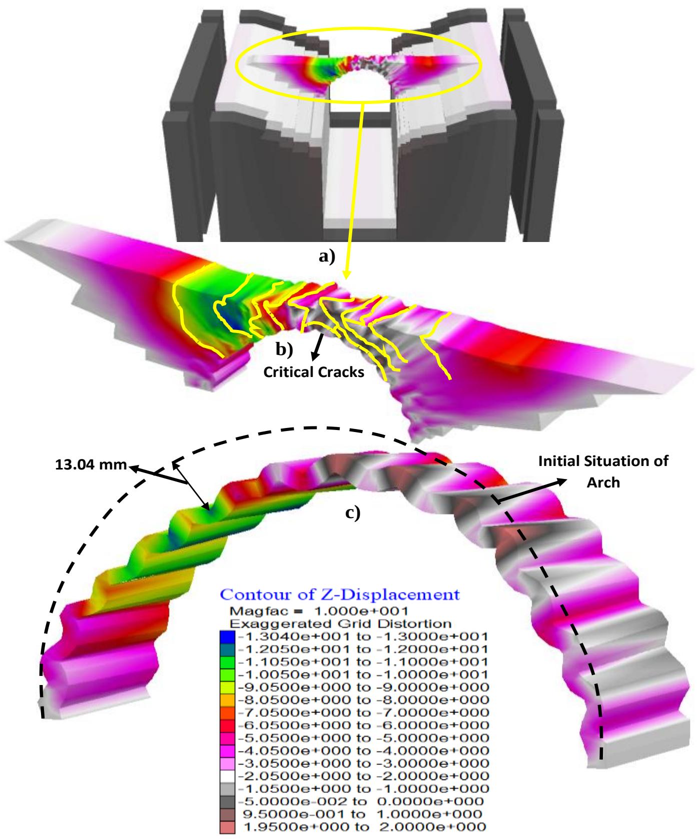

Figure 14. Seismic analysis results (mm) of the Çüngüş bridge for Case 8 (Nurdağı2 earthquake).

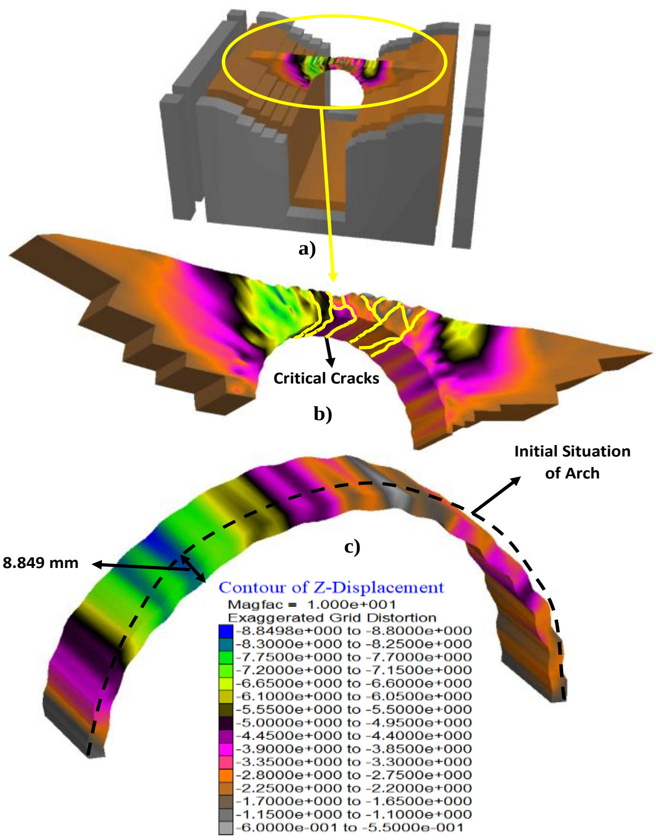

Figure 16. Seismic analysis results (mm) of the Çüngüş bridge for Case 10 (Ekinözü earthquake).

5. Conclusion and Suggestions

In this study, both the long-term creep settlement and earthquake behavior of the historical Çüngüş arch bridge built in the 18th century in Diyarbakır, Türkiye were investigated in detail. The three-dimensional discrete element modeling technique was used while modeling the bridge. Moreover, free field and quiet boundary conditions were applied to the three-dimensional finite-difference model of the bridge, and the seismic behavior of the bridge was investigated under 10 different near-fault earthquakes for the full reservoir situation of the bridge. This study provides new and special contributions to the literature on the examination of creep and seismic behavior of historical bridges. As a result of this study, the following critical results were obtained.

- According to the time-depending creep settlement analyses of the historical Çüngüş stone bridge, it was concluded that the arch (Fig. 4) is the most deformed section of the bridge. During 500 years of creep analysis, the most vertical displacements were obtained in the middle of the arch section of the bridge. Furthermore, the largest vertical displacement values on Point 9 and Point 10 are approximately 6 mm.
- According to the creep settlement analysis results of the Çüngüş stone bridge, it was seen that the changing rate of vertical displacements in the bridge during the first 200 years is very low, and the changing rate in the vertical displacements in the bridge increased between 1973 and 2173. From this result, it was concluded that the changing rate in the vertical displacements of the historical bridge is very low during the first 200 years.
- According to the seismic analysis results, it was understood that the most critical section of the bridge is the arch section (Fig. 4). It was concluded that the seismic vertical displacements in the arch section are higher than the other sections of the bridge. Besides, it was observed that the greatest bending occurred in the middle sections of the arch. According to this result, it has been understood that the arch section of the bridge is the part that needs the most attention for the earthquake strength of historical buildings built on earthquake faults.
- According to the 10 various earthquake analyses, it was observed that the largest displacements and seismic cracks on the bridge occurred in the 2023 Kahramanmaraş (Pazarcık) earthquake. The greatest displacement value that occurred in the middle parts of the bridge during the Kahramanmaraş (Pazarcık) earthquake is 25.604 mm. This value is of great importance for the future and survival of the Çüngüş Bridge.
- It was seen that the most critical cracks that occurred during the earthquake were obtained in the arch section (Fig. 4) of the bridge. According to 10 different earthquakes, it has been observed that there are very large cracks in the middle sections of the arch section of the bridge and smaller seismic cracks at the edges of the bridge. From this result, it was understood that the most critical sections for the crack behavior of historical stone bridges are the arch sections (Fig. 4).

Acknowledgment

The author wishes to express their thanks to the authors of the literature for the supplied scientific aspects and ideas for this study.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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