Academic Journal of Nawroz University (AJNU), Vol.10, No.3, 2022

e-ISSN: 2520-789X

https://doi.org/10.25007/ajnu.v11n3a857

Effect of SSI and Fixed-base Concept on the Dynamic Responses of Masonry Bridge Structures, Dalal Bridge as a Case Study

Halmat Ahmed Awlla [1], Nichirvan Ramadhan Taher(PhD Candidate)[2], Huseyin Suha AKSOY [3],
Anwar Jabar Qadersheen [4]

[1]Department of Information Technology, Choman Technical Institute, Erbil Polytechnic University, KRG, Iraq
[2]Department of Civil Engineering, Faculty of Engineering, Firat University, Elazig, Turkey
[3]Department of Civil Engineering, Faculty of Engineering, Firat University, Elazig, Turkey
[4]Department of Civil Engineering, Faculty of Engineering, Soran University, Erbil, Iraq

ABSTRACT

Historical masonry structures are very important as they carry cultural heritage, so it is important to protect these structures from natural disasters such as earthquakes and transferred to the next generations. It is known that masonry structures are weak against earthquakes, therefore, a suitable analysis method for assessment and retrofitting purposes is a must. Generally, the fixed-base concept is used for analysis and design purposes, however, in reality, the structures are not fixed-base but they are resting on soils. The current study aims to make a comparison study between dynamic responses of fixed base and soil-structure interaction (SSI) models for bridge masonry structures, the historical Dalal bridge was selected as the case study. First, the bridge was modeled as a fixed base model, and then three different soil profiles (hard, medium and soft soils) were added to the underneath of the structure. The numerical models were analyzed under El Centro earthquake record. Results indicating a good agreement between the fixed base and the case of hard soil base. However, considerable differences were observed for medium and soft soil profiles.

Keywords: Dynamic response, Fixed-base concept, Masonry bridge structures, Soil-structure interaction, Solid finite elements.

1. Introduction

There is a huge number of historical bridge masonry structures word wide, these kinds of ancient structures are the most valuable elements of cultural heritage. These types of bridges are made of masonry stones and the main parts of the structures normally contain foundations, arches, spandrel walls and backfill material. A natural disaster such as an earthquake has a great influence on the damage of these significant historic structures. For this reason, it is very important to assess the response of these kinds of buildings to the seismic load to ensure structural integrity (Lubowiecka et al., 2011; Pelà et al., 2013; Pepi et al., 2017; Sevim et al., 2011).

Back to the literature, many studies can be found on the masonry bridge behaviors. (Royles & Hendry, 1991) researched on 24 arch bridges with three different spans, they studied how the limit strength of bridges is influenced by the spandrel walls, the wing walls, and the backfill materials. The researchers concluded that the resistance of the barrel arch is increased by the spandrel and wing walls. (Begimgil, 1995) studied the influence of the restraint of the spandrel wall on a masonry bridge with a span of 1.25 m. It has been noticed that the deflections calculated over the width of the arch are generally greater in the midpoint of the arch. (Boothby et al., 1998) Performed a large-scale bridge under service loads and similar observations for the test results were acquired. (Fanning & Boothby, 2001) worked on the determination of the suitable properties of materials for modeling these kinds of structures. For this purpose, they used the results of the three existent of the full-scale in-service masonry arch bridges. They performed 3D nonlinear finite element analysis. A

Drucker-Prager and smeared cracks materials models were used for backfill materials and masonry, consecutively. After analysis of the bridges under service loads, the comparison was made between the solutions obtained and the results of the field tests of the bridges. (Milani & Lourenço, 2012) studied the 3D behavior of two masonry arch bridges by performing a non-linear static analysis using finite element code. (Sayın et al., 2011) examined the linear and non-linear analysis of the historic Uzunok bridge using a three dimensional finite element model. (Pelà et al., 2013) performed time history and pushover analyses to evaluate the seismic capacity of an existing triple-arched masonry bridge. (Rafiee & Vinches, 2013) studied the mechanical behavior of a standard arch bridge and a stone masonry bridge under various sorts of static loading. (Altunışık et al., 2015) studied the impact of the thickness of the arch on the structural conduct of masonry arch bridges. (Sayin, 2016) assessed the response of a masonry bridge to seismic loads, to this end, they generated records of artificial acceleration taking into account the seismic characteristics of the area where the bridge is located.

However, it is known that, in reality, the dynamic responses of the buildings are affected by the surrounding soil (Kramer, 1996; Wolf & Song, 2002). Understanding the dynamic effects is not easy and it is a rather complex task in theory and practice if appropriate structural modeling is not constructed (Asteris et al., 2014; Giamundo et al., 2014). SSI is very important in the evaluation of particular bridges that are on soft ground (Chouw & Hao, 2008). It has been observed that the SSI has a beneficial and harmful influence on isolated arched bridges depending on the characterization of the seismic movement (Ates & Constantinou, 2011). by performing a complete nonlinear 3D time-history analysis for historical masonry bridge, it was observed that SSI has a considerable effect on the seismic responses in terms of acceleration, displacement, modal forms, frequency in lower modes, the moment of reversal and base shear (Güllü & Jaf, 2016). (Hacıefendioğlu et al., 2015) studied the influence of multi blast-induced ground movement on the dynamic responses of masonry historical bridges. The results showed larger response values for uniform ground movement when compared with the responses obtained from the multi-point blast-induced ground movements. Even though SSI influences the dynamic responses of masonry structures, neither a laboratory test nor a numerical study was available in the literature for comparing dynamic responses of such a fixed base structure with its prototypes resting on different soil profiles (soft, medium, hard soils).

The most suitable tool to evaluate the seismic response of any building is the time-history analysis (nonlinear dynamic analysis). Nonetheless, the nonlinear approach is greatly dependent on the uncertainty of the input parameters and a lot of time is required for the computation, which is why it is considered impractical (Pelà et al., 2009). To understanding the global behavior of buildings, linear (static and dynamic), as well as pushover (nonlinear static) analysis, are utilized (Magenes, 2006). Pushover analysis is usually used to assess the seismic performance of and existing structure, however, the pushover analysis outweighs some of the disadvantages of dynamic linear analysis, thus it is advisable to follow different analysis procedures for the same model and critical discussion needed on the analysis outcomes (Magenes et al., 2010). There are two main methods for nonlinear analysis of frame buildings, lumped plasticity approach and distributed plasticity approach which is so-called (fiber element method) (Ahmed, 2019; M. Karaton & Awla, 2018). But the more exact and detailed method is solid finite element method for analyzing nonlinear cases, which is best applicable for all types of frame and masonry problems. Many structural and material behaviors can be incorporated in the numerical model such as (cracks, concrete-rebar bond, creep, friction, thermal sensation ...etc.). Structural members are discretized into a huge number of solid elements and this makes the method computationally expensive, thus the method is not used for real-scale buildings in everyday engineering analysis and design purposes, it is only utilized for the critical regions of buildings as beam/column intersection points and to the places that are supposed to undergo large inelasticity and deflections (Taucer et al., 1991).

The aim of the current study is to perform linear dynamic analysis through solid finite elements for the 115m long historical Dalal bridge and to make a comparison study between dynamic responses of fixed-base and soil-structure interaction models. For this reason, commercial finite element package SAP2000 was used throughout the modeling and analysis procedures. However, nonlinear analysis is the best and most accurate method for analyzing structures under different conditions and loadings but still, linear dynamic analysis can tell us more about the dynamic characteristics of structures. Moreover, nonlinear dynamic analysis is a straight forward procedure but it does need a considerably long computational time for such full-scale structure.

Dalal Bridge is located in the city of Zakho, Kurdistan region, northern Iraq is one of the ancient masonry stone bridges over the Khabur River. Fig. 1. The bridge is about 115 meters long, 4.7 m wide and 16 meters high, it is accepted to have been first constructed during the Roman time, while the current structure seems to be from a later date.

FIG. 1. THE VIEW OF THE DALAL BRIDGE.

2. NUMERICAL MODELLING

Three different methods are used for modeling masonry buildings: Micro, Simplified micro and Macro modeling Fig. 2. In the Macro modeling method, to reduce the time required for computational efforts as well as least occupying memory size, mortar, brick and stones are treated as one isotropic material because this leads to the use of the minimum finite element numbers. In contrast, in the other two methods, Micro and Simplified micro modeling, mortar, brick and stones are modeled separately because these are more versatile and detailed consequently most accurate and authenticate methods for analyzing these types of structures. Damage patterns, crack phenomenon and many other physical behaviors can be incorporated in the method. Thus, in the Micro modeling methods, larger memory size of and longer computational time are required (Muhammet Karaton et al., 2017; Muhammet Karaton & Çanakçı, 2020).

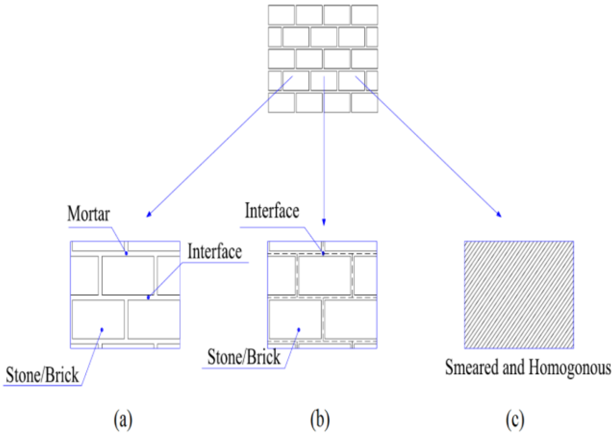


Fig. 2. Masonry building modeling methods; a) micro, b) simplified micro and c) macro modeling (Muhammet Karaton et al., 2017; Muhammet Karaton & Çanakçi, 2020).

The bridge structure was modeled by solid finite elements in a full 3D manner using SAP2000 software package. Generally, SAP2000 only contains elastic eight-node solid brick elements Fig. 3, but the inelasticity behavior can be added to the system, for this purpose the nonlinear link elements are connecting the adjacent solid element nodes. Since the stress-strain nonlinear relationship of the materials are assigned to these nonlinear link elements, the system can simulates certain structural problems (SAP2000, 2009). The inelastic analysis is out the scope of this work but for further studies, it can be investigated. The scope of the current study is up to elastic level only, still, the linear dynamic analysis for masonry structures employing solid elements can be beneficial for analysis, design, strengthening and assessment of masonry buildings.

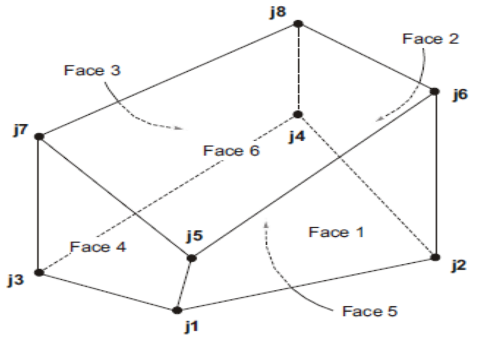


Fig. 3. Eight node solid finite elements (SAP2000, 2009)

In this study four numerical cases were created as case-1, case-2, case-3 and case-4 for fixed-base, hard soil, medium soil and soft soil profiles, respectively. Material properties of arches, spandrel walls, backfill materials and soil profiles were selected depending on the similar studies in the literature. All numerical cases were analyzed under El Centro earthquake acceleration record, the plot is shown in Fig. 4.

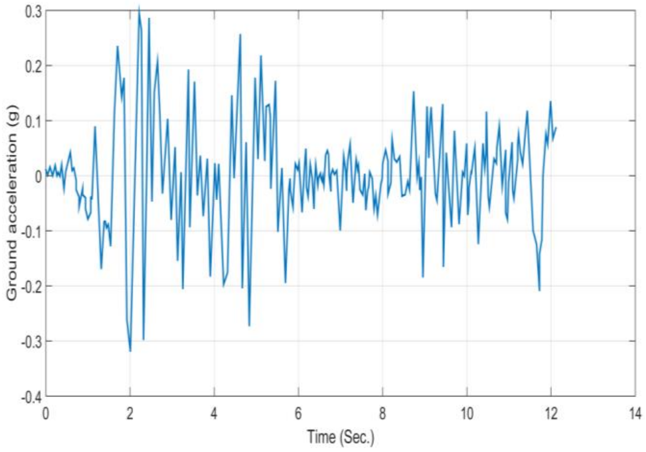


Fig. 4. El Centro acceleration plot.

3. Description of the numerical bridge

The bridge is approximately 115 meters long, 4.7 m wide and 16 meters high and it rests on the rocky layer in nature. The bridge consists of five arches, one high and wide in the middle and other smaller arches on the sides. It was documented by terrestrial digital photogrammetry technology by (K.Pavelka, 2009) as a part of many Czech-Iraqi projects for documentation and reconstruction of monuments and historical buildings in the country Fig. 5.

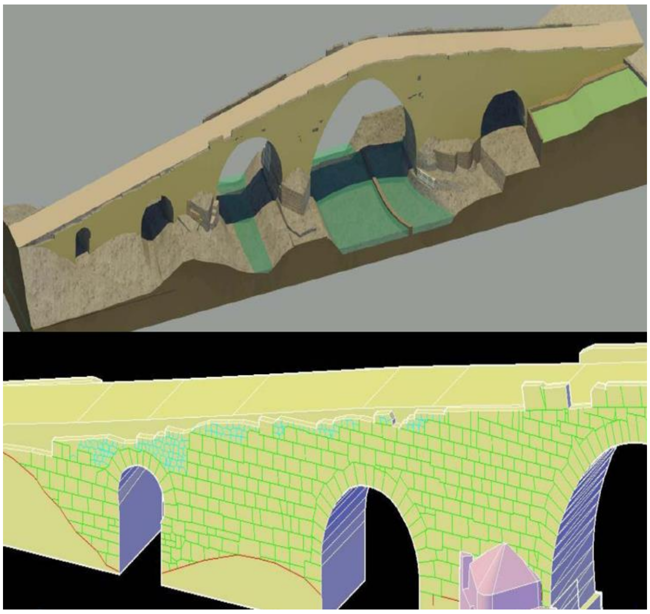


Fig. 5. CAD model of Dalal bridge documented by terrestrial digital photogrammetry technology (K.Pavelka, 2009).

For the numerical case-1, the base of the bridge is assumed to be fully restrained against rotation and translation in all three principal directions, and 10570 solid elements were used for generating the model, finite element model is shown in Fig. 6.

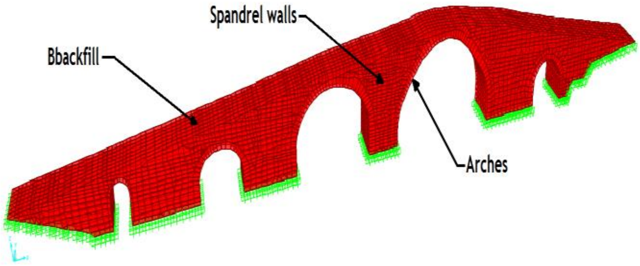


FIG. 6. FINITE ELEMENT VIEW OF DALAL BRIDGE FOR THE FIXED BASE NUMERICAL CASE.

The other three numerical cases were modeled by adding a big soil medium to the underneath of the bridge, the boundary conditions have been decided in accordance with the previous studies in the literature, the dimensions of the substructure soil were calculated exactly as (Güllü & Jaf, 2016). It can be concluded from the earlier studies (Livaoglu & Dogangun, 2007; Park et al., 2013; Reza Tabatabaiefar et al., 2013; Su & Wang, 2013) that the dimensions and boundaries of substructure soil are case dependent, it has been reported (Reza Tabatabaiefar et al., 2013) that acceptable dimensions of the substructure soil should be selected to canceling out any undesirable boundary effects. The length of the substructure soil was taken into account by approximately half of the bridge length 57m beyond the bridge boundaries. The width of the substructure soil is taken by approximately the bridge width in both sides of the bridge. Approximately the dimensions of (229x14.7x28m) and 34277 solid elements were used for substructure soil. Thus the total numbers of 44847 solid elements were used for modeling the SSI numerical cases, the model is shown in Fig. 7.

According to the previous suggestions (Güllü & Jaf, 2016) to achieving more accurate estimations due to the effects of SSI, the roller boundary as supporting boundary conditions was employed for the nodes of the soil vertical faces (FEM mesh), while the fixed boundary was selected for the bottom of the (FEM mesh).

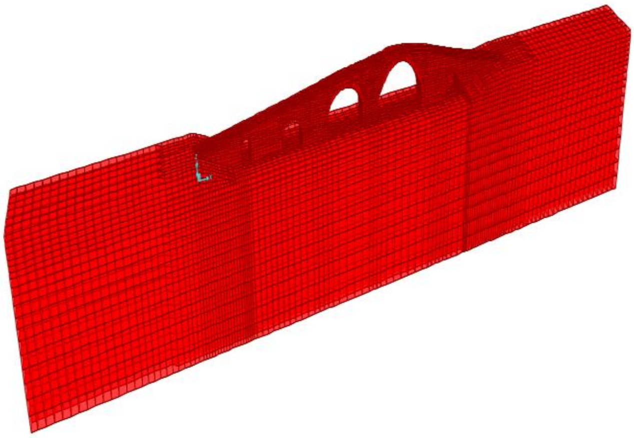


FIG.7. FINITE ELEMENT VIEW OF DALAL BRIDGE FOR SSI NUMERICAL CASES.

SAP-2000 does not include efficient and sophisticated techniques for meshing as available in other software like ABAQUS or ANSYS, instead, the user should carefully add 3D solids by extrusion techniques to the model to the nodes coincide each other and well connected as shown in Fig. 8, otherwise load losing may take place.

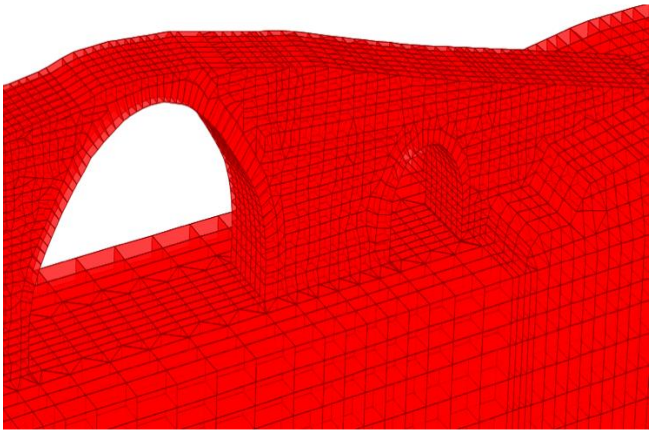


FIG. 8. MESHING DETAILS AND NOD CONNECTIONS FOR THE 3D FINITE ELEMENT MODEL.

Material properties of the bridge and the underneath soil were selected depending on the previous studies. Arch stone, spandrel walls stone and backfill material properties were defined according to (Muhammet Karaton et al., 2017). (Muhammet Karaton et al., 2017) studied Malabadi historical bridge under the effect of seismic loading, they tested the materials of the bridge in laboratory, structural form of the bridge is the same as Dalal bridge which is arch masonry bridge.

Malabadi historical bridge was constructed in the Roman era on Batman river in Turkey. The bridge is about 170 km far away from Zakho on the north-east side. Thus, we have assumed that the mechanical properties of the materials used for the Dalal bridge as same as the Malabadi bridge.

Soil profile properties were also defined according to (Hökelekli & Al-Helwani, 2019). Since the objective of this work is to studying the effects of soil-structure interaction on the dynamic responses of masonry bridge structures, thus using different soil profile properties is a must. In the well-known seismic codes six different soil profiles have been introduced (Very soft, Soft, Stiff, Very Stiff, Rock and Hard rock) among them American Society of Civil Engineers (ASCE), International Building Code (IBC) and Uniform Building Code (UBC). In this study same parameters used in (Hökelekli & Al-Helwani, 2019) were used for (Hard soil, Medium soil and Soft soil) profiles as a representation for all types of soil profiles. The refined material properties are shown in Table 1.

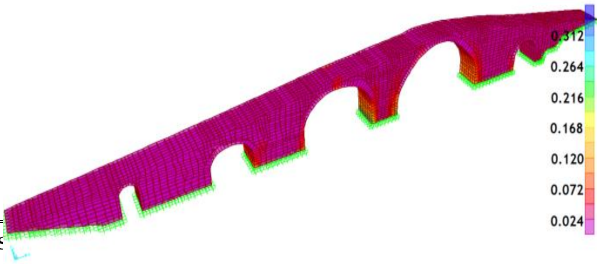
TABLE 1 THE MATERIAL PROPERTIES USED FOR MODELING NUMERICAL CASES.

Material	Density (ton/m^3)	Modulus	
Arches stone	2.502	9574.109	0.28
Spandrel walls stone	2.475	8280.092	
Backfill material	1.8	500	
Hard soil	2.064	5680	
Medium soil	1.864	361	
Soft soil	1.667	34.5	

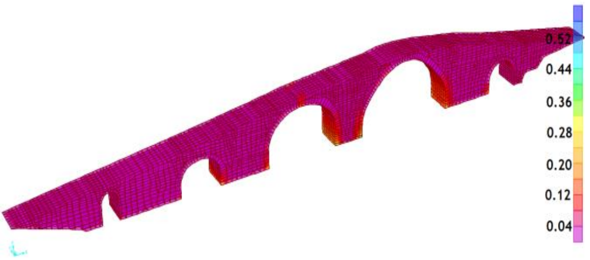
After performing dynamic analysis, the dynamic responses of the structure in terms of displacements and maximum stresses are interpreted.

4. RESULTS AND DISCUSSION

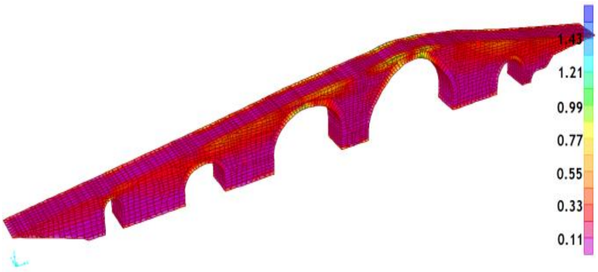
Four numerical model cases were created for performing linear dynamic analysis to the Dalal historical masonry bridge. The first numerical case was idealized as a fixed base, while for the other three cases the SSI was taken into account. Hard soil, medium soil and soft soil profiles were used for modeling the numerical case-2, case-3 and case4, respectively. The numerical cases were analyzed under El Centro acceleration record in the longitudinal direction of the bridge. Dynamic responses in terms of displacements, stresses and natural periods of the SSI numerical models were compared with the fixed base idealized one. According to the obtained results, good agreement was observed between the fixed base and the second numerical case which was rested on hard soil. However considerable differences were seen between fixed base and the two remained numerical cases. The results are indicating that for this typology of structures resting on hard soils can be idealized as a fixed base for simplification in analysis or other purposes. But for structures resting on medium and soft soils, the results will be more accurate if the SSI is considered.



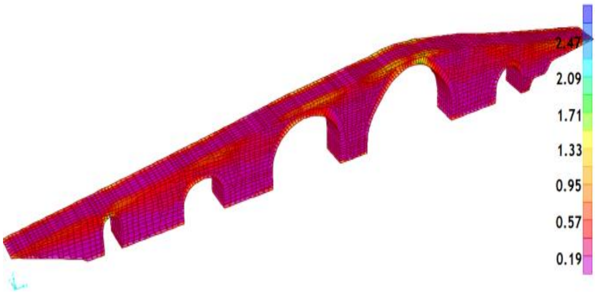
A: Fixed base



B: Hard soil



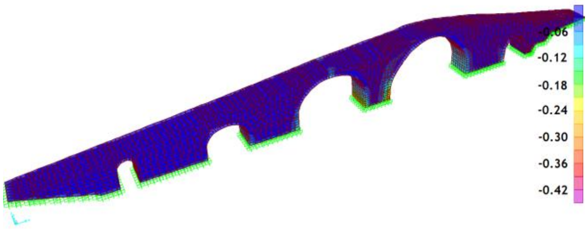
C: Medium soil



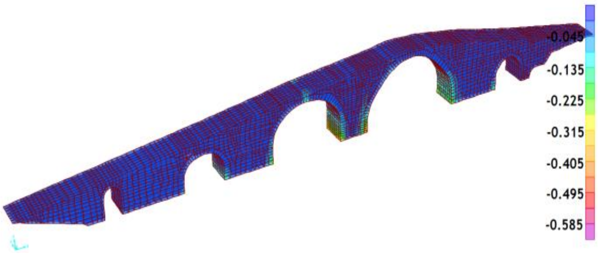
D: Soft soil

FIG. 9. MAXIMUM TENSION STRESS DISTRIBUTION SCALE IN MPA. A) FIXED BASE, B) HARD SOIL, C) MEDIUM SOIL AND D) SOFT SOIL.

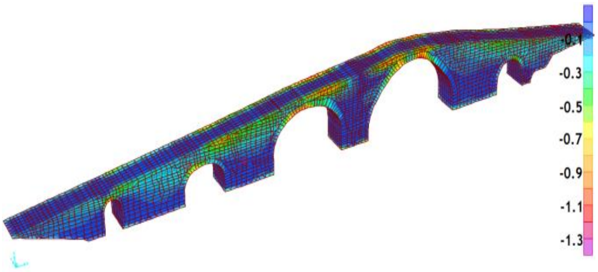
Maximum tension and compression stress distributions in the three-dimensional view are presented in Fig. 9. and Fig. 10. According to the results of the maximum tensile and compressive stresses, a good agreement was observed between the fixed base and hard soil base cases and minimal deviations were observed. However, this ratio of difference is considerably high for the numerical cases resting on medium and soft soils.



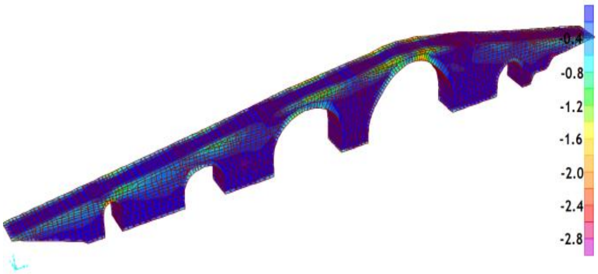
A: Fixed base



B: Hard soil



C: Medium soil



D: Soft soil

FIG. 10. MAXIMUM COMPRESSION STRESS DISTRIBUTION SCALE IN MPA. A) FIXED BASE, B) HARD SOIL, C) MEDIUM SOIL AND D) SOFT SOIL.

The point number 1610 was selected as monitoring displacement point Fig. 11, since it is the highest point. Time history displacements of the fixed base with hard soil, medium soil and soft soils were plotted in Fig. 12. And the maximum displacement values were summarized in Table 2. It can be noticed from the table and the figure that the displacement values are compatible between fixed base and hard soil numerical case. However dramatic changes were observed for the numerical cases resting on medium and soft soil profiles.

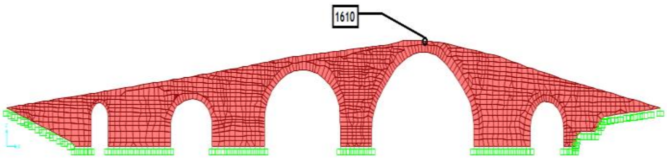
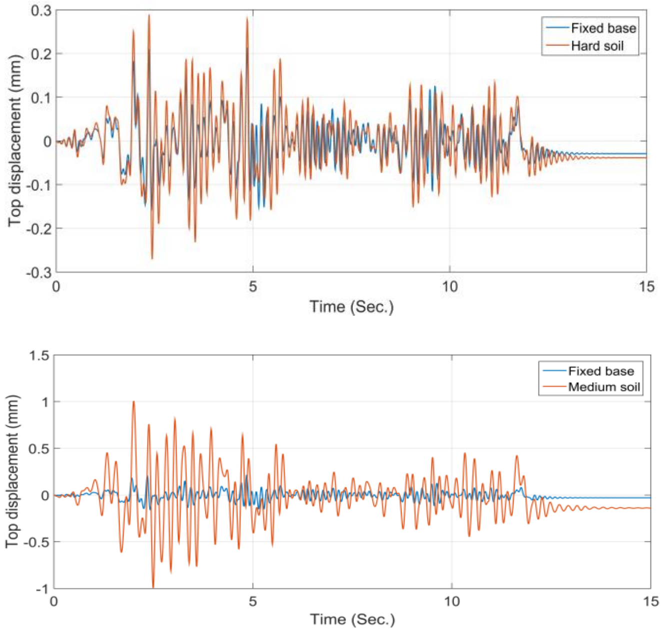


FIG. 11. TOP DISPLACEMENT MONITORING POINT.



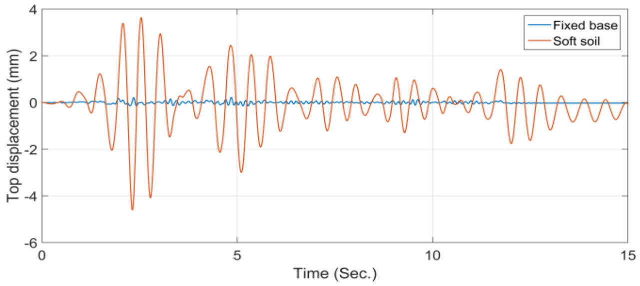


FIG. 12. TOP DISPLACEMENT GRAPH FOR FIXED BASE AND SSI MODELS.

TABLE 2 MAXIMUM DISPLACEMENT VALUE FOR THE POINT 1610

Numerical case	Maximum displacement (mm)	Difference% to Fixed-base case
Fixed-base	0.2135	-----
Hard soil	0.2892	35.4%
Medium soil	1.004	370.2%
Soft soil	4.5644	2037.8%

On the other hand since the natural periods are other important dynamic characteristics of structures. The first three natural periods of the first three mode shapes were compared and presented in Table 3. It is noticed that the natural periods of the fixed base structure very close to the hard base one. However considerable differences were observed for the medium and soft base structures.

TABLE 3 FIRST THREE NATURAL PERIODS (T) IN SECONDS FOR ALL NUMERICAL CASES

Numerical case	T1	T2	T3	Difference% to Fixed-base case T1	T2	T3
Fixed-base	0.227	0.17	0.139	-----	-----	-----
Hard soil	0.257	0.19	0.153	13.2%	11.7%	10.1%
Medium soil	0.49	0.34	0.25	115.8%	100%	79.8%
Soft soil	1.206	0.72	0.576	431.2%	323.5%	314.4%

In the well-known seismic codes as Uniform Building Code (UBC), International Building Code (IBC), American Society of Civil Engineers (ASCE) and others, site classes (soil profiles) are classified depending on the shear wave velocity in the soil ASCE (7-16), Table 20.3-1. Shear wave velocity (Vs), modulus of elasticity (Es), density of soil (ρ), shear modulus (Gs) and Poisson's ratio (ν) are related to each other according to the following two equations.

$$V_s = \sqrt{\frac{G_s}{\rho}} \qquad (1)$$

$$G_s = \frac{E_s}{2(1+\nu)} \qquad (2)$$

By using the two equations, shear wave velocity for Hard soil, Medium soil and Soft soils used in this study were calculated as 1028.8, 267.8 and 75.6 m/sec respectively. Thus, the outcomes of this research in agreement with the results obtained by (Awlla et al., 2020; Galal & Naimi, 2008; Maheshwari & Sarkar, 2011; Reza Tabatabaiefar et al., 2013) when shear wave velocity of a soil class less than 600 m/sec the effect of SSI become significant on the dynamic responses of structures.

The results of the current study showed that SSI has significant effects on the responses of masonry bridge structures resting on different soil profiles under dynamic loading. As presented in Table 2 the maximum displacement percentage difference ratios between (Fixed-base and hard soil), (Fixed-base and medium soil) and (Fixed-base and soft soil) cases is (35.4%, 370.2% and 2037.8%) respectively. On the other side the percentage of difference ratios for the first three natural periods between (Fixed-base and hard soil), (Fixed-base and medium soil) and (Fixed-base and soft soil) cases is (13.2%, 11.7%, 10.1%), (115.8%, 100%, 79.8%) and (431.2%, 323.5% and 314.4%) respectively, Table3. It's obvious from the results that when the obtained dynamic responses of the fixed-base model compared to the SSI cases, good agreement was observed with hard soil profile, however, maximum percentage differences occurred in the soft soil and these values decreased for medium soil profile case. It's because Soft soils have less stiffness when compared to the medium and hard soils, on the other side, Soft soils are highly compressible because of the large percentage of void ratios in it. As presented in Table 1 the modulus of elasticity of hard soil profile is 5680 MPa with Poisson's ratio of 0.3 which is indicates that hard soil is much stiffer than medium and soft soil profiles with less percentage of void ratios and less compressibility behavior, in the consequence the seismic waves will produce less deformation in soil layers, thus the seismic responses of fixed base and hard soil base SSI case are much compatible than other SSI cases. It can be concluded that fixed-base idealization for masonry bridge structures resting on hard soil profiles adequate for analysis, design, assessment and rehabilitation purposes. However this idealization is no longer true for the structures resting on the other soils and SSI shall be considered.

5. CONCLUSION

The objective of this research is to study the effects of SSI on the dynamic responses of masonry bridge structures. For this purpose, the historical Dalal bridge was selected as the case study. Firstly, the bridge was modelled as a fixed-base model, and then three different soil profiles as hard, medium and soft soils were added to the underneath of the structure. The numerical models were analyzed under El Centro earthquake record. As indicated by the outcomes, the following conclusions can be drawn:

- Dynamic responses in terms of displacements, stresses and natural periods of the fixed base are compatible with the hard soil base profile numerical case.
- Considerable differences were observed between the dynamic responses of the fixed base with medium and soft soil base profiles numerical cases.
- Over-all, it can be concluded that for this typology of structures which resting on hard soil profiles can be idealized as a fixed base, however, this simplification leads to overestimating dynamic responses for medium and soft soils.
- The results of the current study in agreement with the results obtained by (Awlla et al., 2020; Galal & Naimi, 2008; Maheshwari & Sarkar, 2011; Reza Tabatabaiefar et al., 2013) when shear wave velocity of a soil profile less than 600 m/sec the effect of SSI become significant on the dynamic responses of structures.
- Dalal bridge rested on a hard and rocky soil profile, thus for the next studies, the structure can be analyzed as a fixed base for seismic capacity assessment or retrofitting purposes.

For the future studies, laboratory tests is recommended to use real properties of materials of the Dalal bridge to providing wider knowledge and better understanding to the dynamic responses.

7. REFERENCES

1. Ahmed, H. (2019). Investigation of a reverse engineering method for determination of material properties of damaged or collapsed reinforced concrete building. (Msc thesis), Firat University, Faculty of Engineering, Civil Engineering Department, Turkey. Retrieved from https://tez.yok.gov.tr/UlusalTezMerkezi/tezDetay.jsp?id=oTG-SJC-ovATsQtvTqqs_g&no=_qMBvwpGFpN-mp63emidog
2. Altunışık, A. C., Kanbur, B., & Genc, A. F. (2015). The effect of arch geometry on the structural behavior of masonry bridges. Smart Struct. Syst, *16*(6), 1069-1089. doi: http://dx.doi.org/10.12989/sss.2015.16.6.1069
3. Asteris, P. G., Chronopoulos, M., Chrysostomou, C., Varum, H., Plevris, V., Kyriakides, N., & Silva, V. (2014). Seismic vulnerability assessment of historical masonry structural systems. Engineering structures, *62*, 118-134. doi: https://doi.org/10.1016/j.engstruct.2014.01.031
4. Ates, S., & Constantinou, M. C. (2011). Example of application of response spectrum analysis for seismically isolated curved bridges including soil-foundation effects. Soil Dynamics and Earthquake Engineering, *31*(4), 648-661. doi: https://doi.org/10.1016/j.soildyn.2010.12.002
5. Awlla, H. A., Taher, N. R., & Mawlood, Y. I. (2020). Effect of Fixed-Base and Soil Structure Interaction on the Dynamic Responses of Steel Structures. International Journal of Emerging Trends in Engineering Research, *8*(9). doi: https://doi.org/10.30534/ijeter/2020/223892020
6. Begimgil, M. (1995). Behaviour of restrained 1.25 m span model masonry arch bridge. Paper presented at the ARCH BRIDGES. PROCEEDINGS OF THE FIRST INTERNATIONAL CONFERENCE ON ARCH BRIDGES HELD AT BOLTON, UK 3-6 SEPTEMBER 1995.

7. Boothby, T. E., Domalik, D. E., & Dalal, V. A. (1998). Service load response of masonry arch bridges. Journal of Structural Engineering, *124*(1), 17-23. doi: https://doi.org/10.1061/(ASCE)0733-9445(1998)124:1(17)
8. Chouw, N., & Hao, H. (2008). Significance of SSI and nonuniform near-fault ground motions in bridge response I: Effect on response with conventional expansion joint. Engineering structures, *30*(1), 141-153. doi: https://doi.org/10.1016/j.engstruct.2007.03.002
9. Fanning, P. J., & Boothby, T. E. (2001). Three-dimensional modelling and full-scale testing of stone arch bridges. Computers & Structures, *79*(29-30), 2645-2662. doi: https://doi.org/10.1016/S0045-7949(01)00109-2
10. Galal, K., & Naimi, M. (2008). Effect of soil conditions on the response of reinforced concrete tall structures to near-fault earthquakes. The Structural Design of Tall and Special Buildings, *17*(3), 541-562. doi: https://doi.org/10.1002/tal.365
11. Giamundo, V., Sarhosis, V., Lignola, G., Sheng, Y., & Manfredi, G. (2014). Evaluation of different computational modelling strategies for the analysis of low strength masonry structures. Engineering structures, *73*, 160-169. doi: https://doi.org/10.1016/j.engstruct.2014.05.007
12. Güllü, H., & Jaf, H. S. (2016). Full 3D nonlinear time history analysis of dynamic soil–structure interaction for a historical masonry arch bridge. Environmental Earth Sciences, *75*(21), 1421. doi: https://doi.org/10.1007/s12665-016-6230-0
13. Hacıefendioğlu, K., Banerjee, S., Soyluk, K., & Köksal, O. (2015). Multi-point response spectrum analysis of a historical bridge to blast ground motion. Structural Engineering and Mechanics, *53*(5). doi: http://dx.doi.org/10.12989/sem.2015.53.5.897
14. Hökelekli, E., & Al-Helwani, A. (2019). Effect of soil properties on the seismic damage assessment of historical masonry minaret–soil interaction systems. Struct Design Tall Spec Build. doi: https://doi.org/10.1002/tal.1694
15. K.Pavelka. (2009). Detailed documentation and 3d model creation of dalal bridge using terrestrial photogrammetry in zakhu, northern iraqi kurdistan. Paper presented at the 22nd CIPA Symposium, Kyoto, Japan. https://www.cipaheritagedocumentation.org/wp-content/uploads/2018/12/Pavelka-Detailed-Documentation-and-3D-Model-Creation-of-Dalal-Bridge-Using-Terrestrial-Photogrammetry-in-Zakhu-Northern-Iraqi-Kurdistan.pdf
16. Karaton, M., Aksoy, H. S., Sayın, E., & Calayır, Y. (2017). Nonlinear seismic performance of a 12th century historical masonry bridge under different earthquake levels. Engineering Failure Analysis, *79*, 408-421. doi: https://doi.org/10.1016/j.engfailanal.2017.05.017
17. Karaton, M., & Awla, H. A. (2018). Numerical investigation of the effect on ultimate loading capacity of different longitudinal reinforcement ratios of a RC portal frame. Journal of Structural Engineering & Applied Mechanics, *1*(3), 147-154. doi: https://doi.org/10.31462/jseam.2018.03147154
18. Karaton, M., & Çanakçı, K. (2020). Micro model analysis of JD6 and JD7 Eindhoven walls with fixed smeared crack model. Journal of Structural Engineering & Applied Mechanics, *3*(1), 18-24. doi: https://doi.org/10.31462/jseam.2020.01018024
19. Kramer, S. L. (1996). Geotechnical earthquake engineering: Upper Saddle River, N.J Prentice Hall 1996.
20. Livaoglu, R., & Dogangun, A. (2007). Effect of foundation embedment on seismic behavior of elevated tanks considering fluid–structure-soil interaction. Soil Dynamics and Earthquake Engineering, *27*(9), 855-863. doi: https://doi.org/10.1016/j.soildyn.2007.01.008
21. Lubowiecka, I., Arias, P., Riveiro, B., & Solla, M. (2011). Multidisciplinary approach to the assessment of historic structures based on the case of a masonry bridge in Galicia (Spain). Computers & Structures, *89*(17-18), 1615-1627. doi: https://doi.org/10.1016/j.compstruc.2011.04.016
22. Magenes, G. (2006). Masonry building design in seismic areas: recent experiences and prospects from a European standpoint. Paper presented at the 1st European Conference on Earthquake Engineering and Seismology.
23. Magenes, G., Galasco, A., Penna, A., & Da Paré, M. (2010). In-plane cyclic shear tests of undressed double leaf stone masonry panels. Paper presented at the 8th International Masonry Conference 2010 in Dresden Dresden.
24. Maheshwari, B., & Sarkar, R. (2011). Seismic behavior of soil-pile-structure interaction in liquefiable soils: Parametric study. International Journal of Geomechanics, *11*(4), 335-347. doi: https://doi.org/10.1061/(ASCE)GM.1943-5622.0000087
25. Milani, G., & Lourenço, P. B. (2012). 3D non-linear behavior of masonry arch bridges. Computers & Structures, *110*, 133-150. doi: https://doi.org/10.1016/j.compstruc.2012.07.008
26. Park, J. H., Choo, J. F., & Cho, J.-R. (2013). Dynamic soil-structure interaction analysis for complex soil profiles using unaligned mesh generation and nonlinear modeling approach. KSCE Journal of Civil Engineering, *17*(4), 753-762. doi: https://doi.org/10.1007/s12205-013-0135-1
27. Pelà, L., Aprile, A., & Benedetti, A. (2009). Seismic assessment of masonry arch bridges. Engineering structures, *31*(8), 1777-1788. doi: https://doi.org/10.1016/j.engstruct.2009.02.012
28. Pelà, L., Aprile, A., & Benedetti, A. (2013). Comparison of seismic assessment procedures for masonry arch bridges. Construction and Building Materials, *38*, 381-394. doi: https://doi.org/10.1016/j.conbuildmat.2012.08.046

29. Pepi, C., Gioffrè, M., Comanducci, G., Cavalagli, N., Bonaca, A., & Ubertini, F. (2017). Dynamic characterization of a severely damaged historic masonry bridge. Procedia engineering, *199*, 3398-3403. doi: https://doi.org/10.1016/j.proeng.2017.09.579
30. Rafiee, A., & Vinches, M. (2013). Mechanical behaviour of a stone masonry bridge assessed using an implicit discrete element method. Engineering structures, *48*, 739-749. doi: https://doi.org/10.1016/j.engstruct.2012.11.035
31. Reza Tabatabaiefar, S. H., Fatahi, B., & Samali, B. (2013). Seismic behavior of building frames considering dynamic soil-structure interaction. International Journal of Geomechanics, *13*(4), 409-420. doi: https://doi.org/10.1061/(ASCE)GM.1943-5622.0000231
32. Royles, R., & Hendry, A. (1991). Model tests on masonry arches. (includes appendices). Proceedings of the Institution of Civil Engineers, *91*(2), 299-321. doi: https://doi.org/10.1680/iicep.1991.14997
33. SAP2000, C. (2009). CSI analysis reference manual for SAP2000: Computers and Structures, Inc.
34. Sayin, E. (2016). Nonlinear seismic response of a masonry arch bridge. Earthquakes and Structures, *10*(2), 483-494. doi: https://doi.org/10.12989/eas.2016.10.2.483
35. Sayın, E., Calayır, Y., & Karaton, M. (2011). Nonlinear seismic analyses of historical Uzunok Bridge. Paper presented at the Seventh National Conference on Earthquake Engineering.
36. Sevim, B., Bayraktar, A., Altunişik, A. C., Atamtürktür, S., & Birinci, F. (2011). Assessment of nonlinear seismic performance of a restored historical arch bridge using ambient vibrations. Nonlinear Dynamics, *63*(4), 755-770. doi: https://doi.org/10.1007/s11071-010-9835-y
37. Su, J., & Wang, Y. (2013). Equivalent dynamic infinite element for soil–structure interaction. Finite elements in analysis and design, *63*, 1-7. doi: https://doi.org/10.1016/j.finel.2012.08.006
38. Taucer, F. F., Spacone, E., & Filippou, F. C. (1991). A fiber beam-column element for seismic response analysis of reinforced concrete structures (pp. 138): Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.
39. Wolf, J. P., & Song, C. (2002). Some cornerstones of dynamic soil–structure interaction. Engineering structures, *24*(1), 13-28. doi: https://doi.org/10.1016/S0141-0296(01)00082-7