Research Article

Hasan Mahdi Al-Jiboury* and Mohammed Kadum Fakhraldin

Finite element analysis of the soil and foundations of the Al-Kufa Mosque

https://doi.org/10.1515/jmbm-2022-0037
received March 16, 2022; accepted April 15, 2022

Abstract: The Great Mosque of Kufa, built in 639 CE and located in Al-Kufa, Iraq, is considered one of the most important mosques in the Islamic world. Because cracks appeared in the historical walls of the Al-Kufa Mosque during the construction of the Muslim Bin Aqeel Underpass, the values and locations of bending moment and shear force may be useful for wall maintenance. So, this study aims to determine the maximum and minimum values and locations of settlement, bending moment, and shear forces under the mosque walls' foundations. Historical references are used to know the previous architectures of the mosque. Also, archaeological investigation reports are adopted to find out the characteristics of the foundations like their dimensions, depths, and materials. Soil investigation reports are used to know the soil layer's properties and parameters. For non-mentioned soil parameters in soil investigation reports, they are determined depending on the theoretical equations, charts, statistical correlations, and models. A model of soil layers, foundations, and walls is conducted and analyzed using finite element software to determine the deformations of soil layers under the mosque's brick foundations and walls. According to the analysis, maximum bending moment and shear force were found under the minaret near the Al-Thuaban gate.

Keywords: Al-Kufa Mosque, archaeological investigations, brick foundations

*** Corresponding author: Hasan Mahdi Al-Jiboury,** Department of Civil Engineering, University of Kufa, Al-Najaf, Iraq,
e-mail: hasssanmahdi@yahoo.com
Mohammed Kadum Fakhraldin: Department of Civil Engineering, University of Kufa, Al-Najaf, Iraq,
e-mail: mohammed.fakhruddin@uokufa.edu.iq

1 Introduction

Al-Kufa Great Mosque is one of the most important and famous mosques in the Islamic world. It is the fourth mosque in Islam after Al-Masjid Al-Haram in Mecca, Al-Masjid Al-Nabawi in Al-Madina, and Al-Aqsa Mosque in Jerusalem. The Great Mosque of Kufa is considered one of the earliest mosques in Iraq, which was built in 639 CE (17 AH). Presently, Al-Kufa Great Mosque includes nine sanctuaries, four minarets, and seven entrances. (On the northern side, Al-Thuaban Gate and Al-Rahma Gate are located; on the western side, Al-Huja Gate is located; and on the eastern side, four small gates connecting the mosque courtyard and Muslim Bin Aqeel courtyard are located). On the eastern side of the mosque is the Muslim Bin Aqeel courtyard, which contains the holy shrines of Muslim Bin Aqeel, Hani Bin Erowa, and Al-Mukhtar Al-Thaqafi as shown in Plate 1, which shows Al-Kufa Great Mosque and the golden dome of Muslim Bin Aqeel holy shrine. Outside the mosque, on the southern side, lies Emirate Palace, which served as the ruler's residence palace in the past. Al-Kufa Mosque is located in Al-Kufa city that is located about 160 km to the southwest of Baghdad, and about 10 km to the northeast of Imam Ali's holy shrine in Al-Najaf Province. The Kufa city elevation is about 22 m above the sea level. The Euphrates River is located about 1 km from the west side of the great mosque. To the northeast side at about 20 km is located a lake locally called Baher Al-Najaf, which has salt water.

2 Historical background

Saad Bin Abi Waqass began the construction of the inclusive city in the middle of Iraq as per the orders of Khalifa Umar Ibn Al Khattab to be a military base for his army, after Al-Qadisiyyah Battle in 639 CE (17 AH) and to be the capital for the Muslims instead of Al-Madaen city. They first built the mosque, which could hold up to 40,000 soldiers, and then they planned and built the city [1].

Plate 1: Al-Kufa Great Mosque.

At that time, they did not build any walls surrounding the mosque but just constructed a canopy in front of the mosque on the Qibla side [2] and dug a trench around the mosque as borders [3]. The mosque remained in its original dimensions and construction until the reign of Ziyad ibn Abihi in 672 CE (50 AH), when it was rebuilt, altered, extended, and developed. The mosque's structure was strengthened and fixed by piercing and filling the columns with lead and iron. The roof was elevated to 30 arms (about 15 m) in height into the sky [3]. The traveler Bin Jubayr visited Al-Kufa city in 1184 (562 AH) and described the great mosque. He said that the mosque was large and on the Qibla side, there are five spans of roofing and on the other three sides, there are two spans. These roofs stand on very high columns made of stones and fixed by piercing and filling with lead [4].

In 1256 (656 AH), the Mongol Ilkhanate empire was created in Iraq. During the era of ruler Abaqa Khan, the Mongol Ilkhanate empire took care of the Al-Kufa Mosque after it had been neglected throughout the Abbasid era. One of the most important things got from this architecture is the walls of the current mosque [5]. Sayed Mohammed Mahdi Baher Al-Eloom in 1767 (1181 AH) filled the mosque's ground with new and clean soil after groundwater appeared on the surface. The soil used to fill the mosque was around 5–6 m deep [1]. The Dawoodi Bohra carried out a large renovation project in Al-Kufa Mosque from 1998 to 2009. The renovation included destroying the rooms, columns, sanctuaries, pavement, roofing, and gates except for the historic walls that surrounded the mosque and the gate and minaret of Al-Thuaban Gate. The Dawoodi Bohra built a new concrete structure from the ground up, including foundations, columns, and roofing. The mosque courtyard was also excavated to a depth of roughly 1.5 m, filled with new soil, reinforced and then poured with concrete, and finished with white marbles. The renovation also included the construction of two new square-shaped minarets with a height of about 30.8 m [5].

3 Archaeological investigations

In 1938, the Iraqi Directorate of General Antiquities conducted archaeological excavations in and around Al-Kufa Mosque. The investigations revealed that the mosque was built on the roughly square ground with a 17-degree deviation from the Qibla angle. Minor discrepancies between the mosque's four walls were also discovered. The southern side (facing the Qibla) stretched about 110 m. The back wall was 109 m long, while the other two side walls were 116 m long. These four walls were tall and were supported from the outside by semi-circular towers. There were five semi-cylindrical towers on the southern side, seven on the northern side, seven on the eastern side, five on the western side, and one in each corner [6]. Figure 1 shows the as-built drawing plan of the Al-Kufa Mosque.

4 The foundations and the walls

The archaeological excavations revealed the foundation under the wall as follows:

(a) The wall's foundations run down to a depth of almost 5.5 m.
(b) When the foundation ascends to the height of 2.6 m, the wall is pushed back, leaving a 60 cm wide bench alongside it.
(c) The tower's foundation rises in a square form to a height of 3.76 m and then turns around as shown in Plate 2.
(d) The current mosque's floor is approximately 4.5 m higher than the foundations.

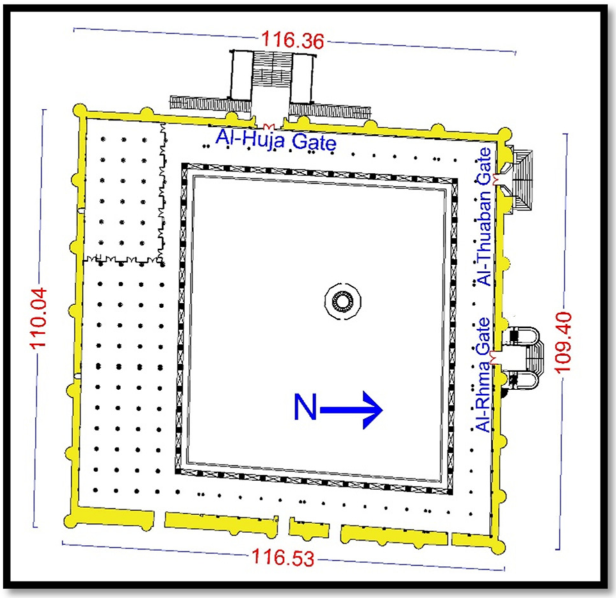

Figure 1: As-built drawing plan of Al-Kufa Mosque.

(e) A square brick with dimensions of about 37 cm × 37 cm × 9 cm and a gypsum mortar was used for the construction works [5].

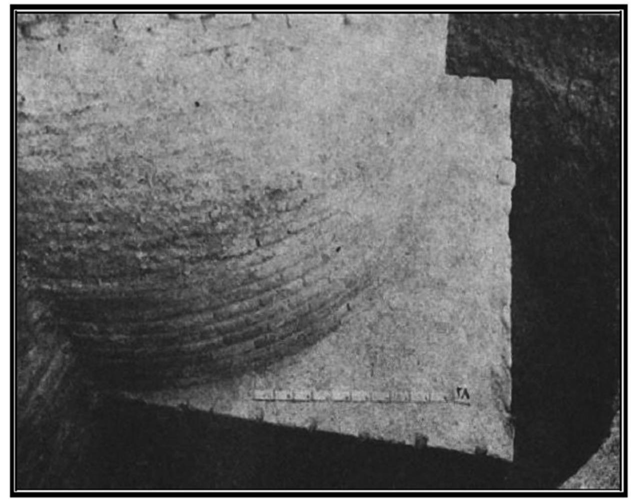

Plate 2: The foundation of a tower in Al-Kufa Mosque according to the archaeological investigation in 1938.

Drawings of the sections of the wall, towers, and foundations that surround the Al-Kufa Mosque based on the as-built drawing and archaeological investigation data are shown in Figure 2.

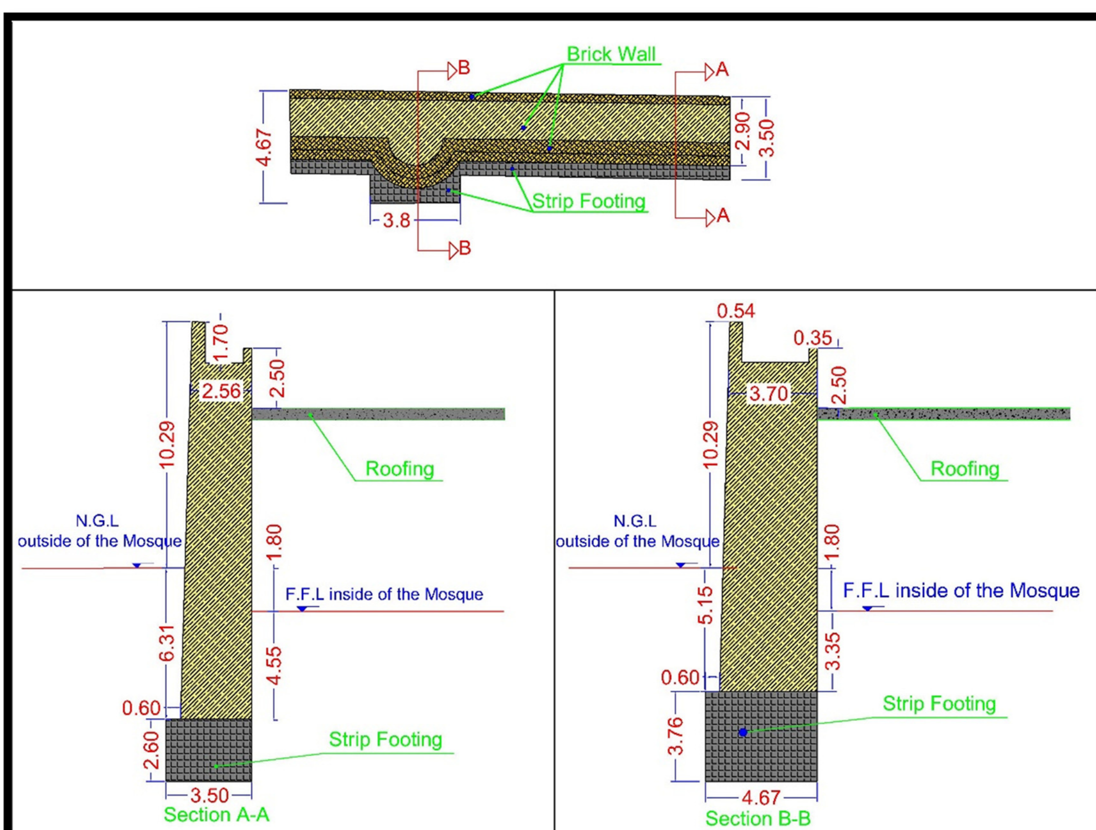

Figure 2: The wall and foundation details of Al-Kufa Mosque.

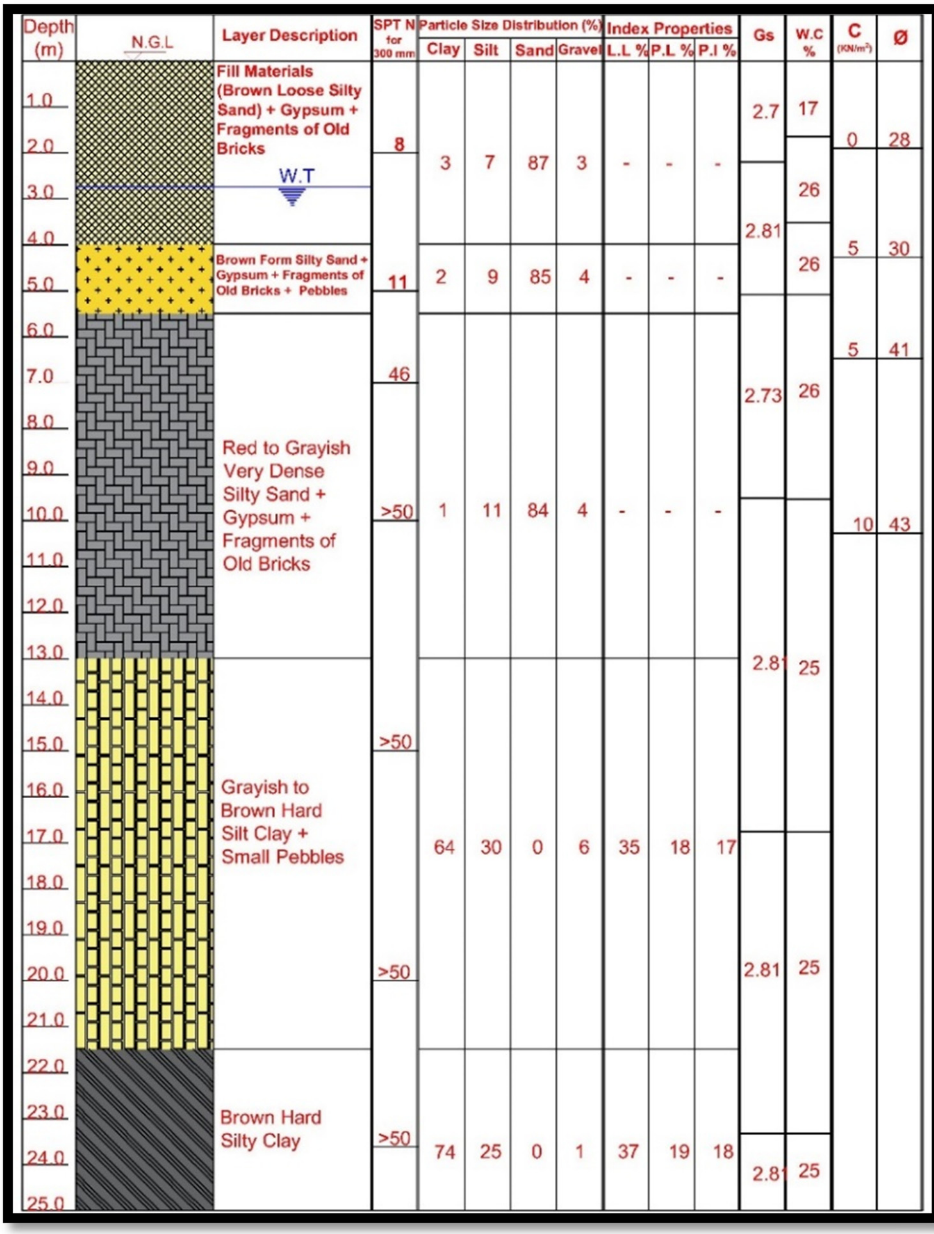

Figure 3: Soil profile of Al-Kufa Mosque.

5 Soil profile

In 2004, the Iraqi National Center for Research and Construction Laboratories – Babylon Department conducted two site investigations at Dawoodi Bohra's request in Al-Kufa Mosque. First site investigations were conducted inside the mosque (in the mosque's courtyard), with ten boreholes bored to a depth of 10 m from the courtyard surface (at that time, the elevation of the courtyard surface was about 2 m below the outside elevation). The second site investigation took place outside the mosque with two boreholes drilled near Al-Huja Gate and one borehole drilled near Al-Rahma Gate to a depth of 7 m below the surface level. In February 2012, the Al-Najaf Technical Institute's Consultant and Scientific Services Bureau conducted site investigations near the Al-Kufa Mosque for the designing and construction of the Muslim Bin Aqeel Underpass. Five boreholes were drilled down to a depth of 20–25 m below street level. Figure 3 shows the soil profiles of the strata of the Al-Kufa Mosque. Plate 3 shows the Al-Kufa Mosque and Muslim Bin Aqeel Underpass which is about 50 m away from the historical walls.

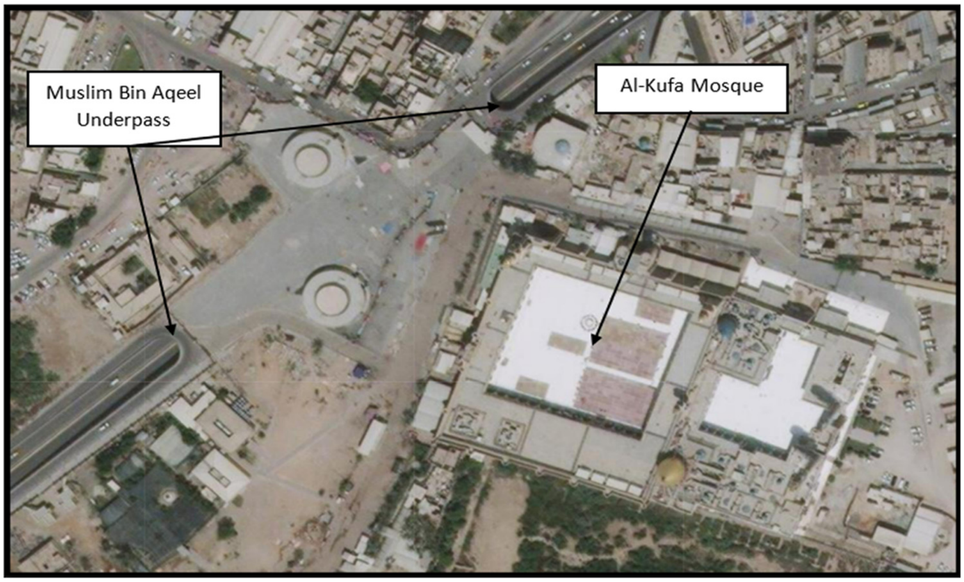

Plate 3: Aerial photo in 2021 illustrates Al-Kufa Mosque and Muslim Bin Aqeel Underpass.

6 Soil parameters

6.1 Poisson's ratio (μ)

Bowles [7] suggested the values of Poisson's ratio (μ) depending on the type of soil. Kumar *et al.* [8] proposed charts and correlations depending on 300 pairs of data for calculating the Poisson's ratio (μ) depending on SPT N value and soil type. Depending on refs. [7,8], we can estimate Poisson's ratio (μ) for the soil profile as summarized in Table 1.

6.2 Modulus of elasticity (E)

Budhu [9] proposed a table for the range of modulus of elasticity (E) based on its type and compactness. The modulus of elasticity (E) for the soil profiles in the Al-Kufa Mosque may be estimated by using ref. [9], as shown in Table 1.

6.3 Void ratio (e)

Fratta *et al.* [10] presented a table for the range values of dry density, saturated density, void ratio, and porosity according to the soil type. For the soil profile of Al-Kufa Mosque, we can calculate the void ratio (e) depending on ref. [10] for dry soil and for saturated soil we can use the following equation:

$$e = \frac{\mathrm{Gs} \cdot W}{S}, \tag{1}$$

and for saturated soil (s) it equals to (1). So, the equation will be:

$$e = \mathrm{Gs} \cdot W. \tag{2}$$

The void ratio for the soil profile layers of the Al-Kufa Mosque are illustrated in Table 2.

Table 1: Poisson's ratio (μ) and modulus of elasticity (E) for the soil profiles in Al-Kufa Mosque

Soil layer	Depth (m)	Soil type	SPT N value	Poisson's ratio (μ)	Selected modulus of elasticity (E) in MPa
1	0–4	Loose silty sand	8	0.28	10
2	4–5.5	Medium silty sand	11	0.31	20
3	5.5–10	Very dense silty sand	46	0.43	70
4	10–13	Very dense silty sand	>50	0.45	80
5	13–21.5	Hard silty clay	>50	0.45	100
6	21.5–25	Hard silty clay	>50	0.45	100

Table 2: Soil properties of the soil layers for the Al-Kufa Mosque profile

Soil layer	Gs	*W* (%)	Dry unit weight (kN/m^3)	Saturated unit weight (kN/m^3)	Void ratio (*e*)	Selected coefficient of permeability (*k*) in cm/s	*c* (kN/m^2)	Ø
1	2.7	17	15	19.444	0.8	0.002	0	28
2	2.81	26	16.242	20.462	0.73	0.0015	5	30
3	2.73	26	15.965	20.117	0.71	0.001	10	41
4	2.81	26	16.242	20.462	0.73	0.001	10	43
5	2.81	25	16.53	20.647	0.7	0.000001	290	—
6	2.81	25	16.53	20.647	0.7	0.000001	290	—

6.4 Unit weight (*γ*)

Budhu [9] provided the following theoretical Eqs. (3) and (4) for calculating the dry and saturated unit weight of the soil layers:

$$\gamma \text{ dry} = \frac{\text{Gs} * \gamma w}{1 + e}, \tag{3}$$

$$\gamma \text{ sat} = \frac{\text{Gs}+e}{1 + e}\gamma w. \tag{4}$$

Depending on Eqs. (3) and (4), the dry soil and saturated unit weights were calculated for the soil profile layers of the Al-Kufa Mosque as listed in Table 2.

6.5 Coefficient of permeability (*k*)

Harr [11] proposed a range of the coefficient of permeability for common soil types. Depending on ref. [11], the coefficient of permeability for the Al-Kufa Mosque's soil profile may be estimated as shown in Table 2.

6.6 Shear strength parameters

The shear strength parameters (*c* and *Ø*) depending on the direct shear test are provided in the soil profile but not to all layers. Puri *et al.* [12] developed models and statistical correlations to estimate many soil parameters by employing the SPT *N* values. Puri *et al.* [12] used 2,067 datasets from 1,053 boreholes bored to the depth of 50 m in Haryana, India. Turner [13] proposed a table for the range of cohesion and unconfined compression strength of the soil depending on the SPT *N* values. The results from the direct shear test for the layers provided in the site profile report may be used for the soil profiles of the Al-Kufa Mosque. For layers 5 and 6, the statistical correlations proposed by Puri *et al.* [12] were applied to estimate the cohesion (*c*) based on the SPT *N* values then the estimated values were compared with the range of cohesion described in [13] as shown in Table 2.

7 Analysis

The analysis of the Al-Kufa Mosque walls and foundations was done by using the finite element method with the finite element software. The representation of the walls and foundations in finite element software was achieved for the western and northern walls because the other two walls (southern and eastern walls) are symmetric to the western and northern walls. Figure 4 shows the representation of the soil layers, foundations, and walls. The representation of the soil profile depends on the soil parameters calculated above with the Mohr–Coulomb Model.

Also, the dimensions of the footing of the walls and towers of the mosque with brick material are calculated with the Linear Elastic Model. Khalifa and Al-Wazni [14] made testing and comparisons between historical and traditional masonry brick for different properties like its compressive strength for brick unit and mortar, density,

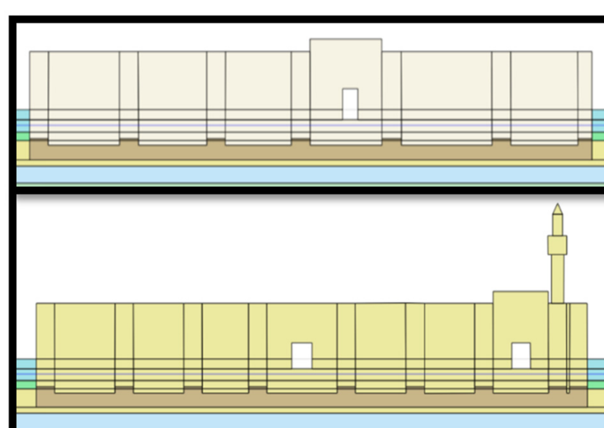

Figure 4: The soil layers, foundations, and walls of Al-Kufa Mosque represented in finite element software.

and modulus of elasticity. The historical brick units were taken from the structure of Imam Ali's holy shrine (built 300 years ago). The testing of the historical brick revealed the following:

- Modulus of elasticity (E) = 3387 MPa
- Unit weight (γ) = 15.24 kN/m^3, and
- Poisson's ratio (μ) = 0.25.

These values were adopted in the analysis.

8 Results and discussion

The deformations, bending moment, and shear force for the soil layers, foundations, and the walls for the northern wall and western wall of the Al-Kufa Mosque are calculated and summarized in Figures 5–8 and Table 3.

For the northern wall, the maximum positive bending moment was under the minaret with the value of 1,229 kN m

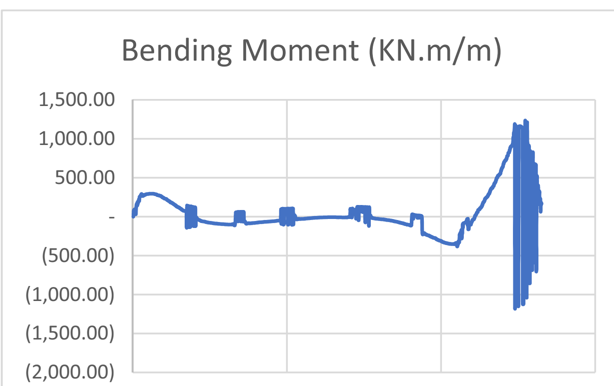

Figure 5: Bending moment distribution under the footing of the northern wall.

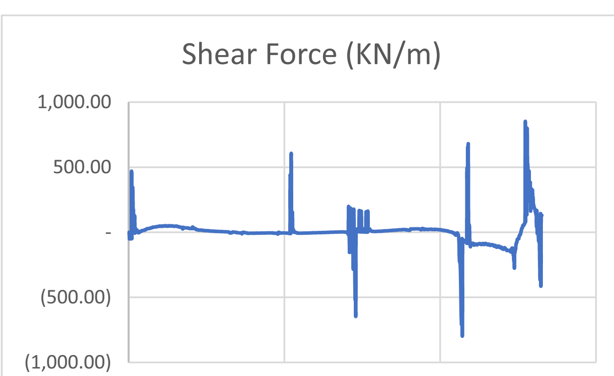

Figure 6: Shear force distribution under the footing of the northern wall.

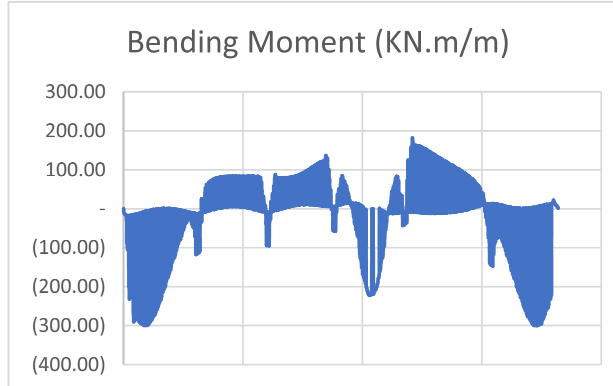

Figure 7: Bending moment distribution under the footing of the western wall.

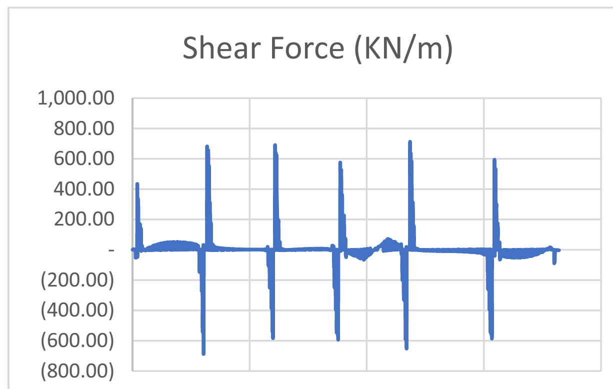

Figure 8: Shear force distribution under the footing of the western wall.

and the maximum negative bending moment value was −1,172 kN m which is located under the footing before the minaret as shown in Figure 5. The maximum positive shear force was under the minaret with the value of 866 kN/m and the maximum negative shear force was under the seventh tower before the gate with the value of −822 kN/m as shown in Figure 6. For deformation, the maximum settlement was 21 mm and located under the second tower near the minaret.

For the western wall, the maximum positive bending moment was under the fifth tower after the gate with the value of 152.54 kN m and the maximum negative bending moment value was −280.89 kN m, which is located before the last tower as shown in Figure 7. The maximum positive shear force was under the fifth tower with the value of 752.9 kN/m and the maximum negative shear force was under the second tower with the value of −738.9 kN/m as shown in Figure 8. For deformation, the maximum settlement was 17.7 mm and located near the gate under the fifth tower.

Table 3: Deformation, bending moment, and shear force values for the northern wall and western wall of the Al-Kufa Mosque

	Northern wall		Western wall	
Deformation	*x*-Direction	Max. value = 10.3 mm Min. value = −8.43 mm	*x*-Direction	Max. value = 8.15 mm Min. value = −8.14 mm
	y-Direction	Max. value = 5.33 mm Min. value = −21 mm	*y*-Direction	Max. value = 4.47 mm Min. value = −17.7 mm
Bending moment	Max. value = 1,229 kN m/m Min. value = −1,172 kN m/m		Max. value = 152.54 kN m/m Min. value = −280.89 kN m/m	
Shear force	Max. value = 866 kN/m Min. value = −822 kN/m		Max. value = 752 kN/m Min. value = −738.9 kN/m	

Figures 5–8 show that the values of shear force and bending moment are fluctuating from negative to positive and vice versa near the towers due to the huge weight of the towers, and subsequently increase toward the gates and minaret. For the deformation, the values of the settlement are (21 mm) in the northern wall under the minaret and (17.7 mm) near the Al-Huja gate in the western wall, and these values occurred because of the high forces that are applied to the foundations in these places. According to the Iraqi Code of Foundations and Retaining Walls [15], the total settlement of shallow foundations must not exceed 32 mm in sandy soil and 45 mm in clayey soil. When the findings of the analysis are compared to the limitations in [15], it is regarded as permissible.

9 Conclusion

1. Historical references and archaeological investigation reports are essential for understanding the historical architecture of antiquity structures, as well as foundation characteristics such as materials, size, and depth. While the as-built drawings are required to provide accurate dimensions of the building elements.
2. If the soil investigation report does not provide all the soil values, then additional properties can be determined using theoretical formulae, tables, charts, statistical correlations, and models based on the SPT N value or soil types.
3. The analysis showed that the bending moment and shear force varied under the towers that are surrounding the walls of the mosque due to the high weight of the towers.
4. The maximum values of bending moment, shear force, and settlement are under the minaret near the Al-Thuaban gate.
5. The values of deformations (settlement) are accepted according to the Iraqi Code of Foundations and Retaining Walls (2015).

Acknowledgments: The authors express their gratitude to the General Secretariat of Al-Kufa Mosque for assisting them and providing all of the required data and reports for the completion of this work.

Funding information: The authors state no funding involved.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: Authors state no conflict of interest.

References

[1] Al-Jiboury KS. Al-Kufa Mosques: An illustrated historical study of the mosques of Kufa from the first century AH to the present. Printed by Dar Al-Nuaman; 1977.
[2] Al-Hamawi Y. Dictionary of countries. Printed by Dar Sadir; Beirut, Lebanon; 1993.
[3] Al-Tabari MI. History of the nations, the Messengers and the Kings. Printed by Dar Ehiaa Al-Turath Al-Arabi; Beirut Lebanon; 2008.
[4] Ibn Jubayr M. The Journey of Ibn Jubayr. Printed by Dar Sadir; Beirut, Lebanon; 1993.
[5] Nabil Abdul Hussein Rahi. Al-Kufa Mosque, the architectural development with a comparative study of the current architecture with the historical accounts of the planning and architecture of the mosque. Al-Adab J. 2018 Sep 1;126:178–91.
[6] Al-Janabi K. Planning the city of Kufa from historical and archaeological references. Printed by The Iraqi Complex; Baghdad, Iraq; 1967.
[7] Bowles JE. Foundation analysis and design. 5th ed. Singapore: McGraw-Hill Companies Inc. 1997.
[8] Kumar R, Bhargava K, Choudhury D. Estimation of engineering properties of soils from field SPT using random number generation. INAE Lett. 2016 Dec;1(3):77–84.
[9] Budhu M. Soil mechanics and foundations. 3rd ed. New York, United States: John Wiley & Sons, inc; 2011.

[10] Fratta D, Aguettant J, Roussel-Smith L. Introduction to soil mechanics laboratory testing. Boca Raton, Florida, USA: CRC Press; 2007 May 21.
[11] Harr ME. Groundwater and seepage. New York, USA: Dover Publications Inc.; 1991.
[12] Puri N, Prasad HD, Jain A. Prediction of geotechnical parameters using machine learning techniques. Proc Comput Sci. 2018 Jan 1;125:509–17.
[13] Turner JM. Excavation systems planning design, and safety. New Yourk, USA: McGraw Hill Professional; 2008 Jul 1.
[14] Khalifa H, Al-Wazni S. Experimental testing and comparison between historical and traditional masonry brick. J Phys: Conf Ser. 2021;1973:012214.
[15] Iraqi Code of Foundations and Retaining Walls, IBC 302; 2015.