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PLAXIS 3D numerical analysis of complex geotechnical problems of colossal built heritage

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Abstract

The paper aims to contribute to the preservation of high valuable historic masonry structures and historic urban landscapes through the combination of geotechnical, structural engineering. The main objective of the study is to conduct finite element analysis (FEA) of bearing saturated soft clay soil problems and induced structural failure mechanisms. This analysis is based on experimental and numerical studies using coupled PLAXIS 3D FE models. The paper presents a geotechnical analytical model for the measurement of stresses, deformations, and differential settlement of saturated clay soils under colossal stone/brick masonry structures. The study also discusses the behavior of soft clay soils under Qasr Yashbak through numerical analysis, which helps in understanding the studied behavior and the loss of soil-bearing capacity due to moisture content or ground water table (G.W.T) changes. The paper presents valuable insights into the behavior of soft clay soils under colossal stone/ brick masonry structures. The present study summarized specific details about the limitations and potential sources of error in Finite Element Modeling (FEM). Further field research and experimental analysis may be required to address these limitations and enhance the understanding of the studied soft clay soil behavior. The geotechnical problems in historic monuments and structures such as differential settlement are indeed important issues for their conservation since it may induce serious damages. It deserves more in-depth researches.

Keywords Qasr Yashbak, Soil-structure interaction, Stone masonry structures, Soil settlement, PLAXIS 3D FE models, Consolidation settlement, Constitutive model, Geotechnical modeling, Soil bearing capacity

Introduction

This study represents a pilot study on the combination of geotechnical engineering, structural engineering and geophysics and their contributions for the preservation of high valuable historic masonry structures (HMS) and historic urban landscapes (HUL).

The present study introduces an attempt to analyze a coupled PLAXIS 3D FE model to simulate subsurface problems and deformation and stress analysis of multilayer stone masonry structures of Qasr Yashbak in Cairo, which are loaded in-plane and out-of-plane. Yashbak Palace, also known as Prince Qawson's Palace, now it is a semi-ruined palace in medieval Cairo, Egypt. Originally it built between 1330 and 1337 AD for a Mamluk prince known as Qawson. This palace was restored and expanded again in the 1680 s by Prince Yashbak al-Mahdi during the reign of Sultan Qaytbay. This unique Mamluk palace suffers different serious geo-environmental and geophysical hazards in particular the severe and powerful seismic events like Dahshuor earthquake in 1992 AD, also the rising of the ground water table (G.W.T) associated with the bearing soil differential settlement.

The main objective of the present study is the finite element analysis (FEA) of bearing saturated soft clay soil problems and induced structural failure mechanisms that have been observed and calculated in experimental and numerical studies based on coupled PLAXIS 3D FE (Digital Stability Analysis) models.

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Advanced Mohr–Coulomb modeling of the soft clay soil was used during the different stages of the numerical finite analysis.

Numerical and experimental analysis allowed us to: (I) Identify the failure mechanism of this unique architectural heritage, (II) Estimate the deformation present in the ground, (III) stress and strain analysis of the superstructure, (IV) Determine the ultimate load that it can bear under its current conditions.

The results are discussed in relation to the stress–strain behavior and volumetric behavior of the soft clay soil. Therefore, it can be concluded that modeling the behavior of the saturated soft clay soil in Qasr Yashbak area through numerical analysis is suitable for understanding the studied behavior of this type of saturated soft clay soil.

Further research and analysis may be required to enhance the understanding of the studied behavior.

While FEM analysis software such as PLAXIS 2D/3D, GEO5, FLAC 2D is fairly new geotechnical engineering software, a lot of work has been done on above ground structures, underground structures, deep excavation and tunneling.

Soft clay soil is considered one of the worst types of foundation materials due to its severe compressive behavior and low shear strength, especially in the case of high groundwater levels and increased moisture content. It is known that this type of soil causes many structural and geotechnical problems for any type of structure on which it rests, whether built heritage or modern buildings.

Soft clay soils in Egypt are found over a large area in the Nile Valley and the Egyptian Delta, especially in historic Cairo, where many Coptic and Islamic archaeological and historical buildings suffer from these geotechnical problems, which are difficult to deal with if they actually exist. Egyptian built heritage is extending from the south to the far north. The thickness of the soft clay soil ranges from 1 to 11 m, and is found at depths ranging from 3 to 10 m below the ground surface.

Historical shallow foundation (strip or isolated footings) subsidence or settlement on saturated clay bearing soil consists mainly of "immediate" settlement due to deformations occurring at a constant soil volume without change of water pore pressure, and "consolidation" settlement due to volume reduction resulting from dissipation of pore water pressures. This last component therefore depends on the pore pressures created by the foundation and structure loading, and these pore pressures themselves depend on the clay type and the clay mineral.

Differential settlement of the bearing soft clay soil under the historic buildings in Cairo usually occurs as a result of irregular movement of the underlying soft clay soil (the soil settles at different rates). This type of settlement can destroy foundations and distort the load-bearing walls in heritage buildings. Additionally, in the case of isolated footings, each isolated footing may settle at a different rate, which is completely different from settlement that would occur for a slab or raft foundation in modern buildings.

Primary consolidation settlement of bearing saturated clay soil occurs due to reduced volumes or pores between soil particles due to applied loads or changes in moisture content and escape of pore water. Loss of soil moisture causes consolidation settlement. When moisture accumulates in the soil, and when moisture is expelled, the soil loses volume and consolidates. In adverse conditions, when there is a buildup of moisture in the soil, small clays and silts, previously used to fill the voids between larger soils and provide additional structural support, flow into the ground when the moisture finally recedes. This will cause the soil to lose its bearing capacity. Also loading and unloading of soil due to the moisture content changes can affect seriously the bearing capacity of the bearing soil.

Analytical and numerical methods are common ways to predict soil and structure settlement, but they rely on some assumptions and simplifications that may not match reality [1–4]. Therefore, both analytical and numerical methods need to be selected and evaluated according to specific engineering conditions and monitoring data. To better capture the patterns in the monitoring data, many researchers are turning to machine learning methods.

In Islamic Cairo, saturated soft clay soil is consolidated under applied loads from historic buildings. All shallow foundations settle when the soil around and under the foundation adjusts to the loading. Historic buildings with light loads or built on rock may experience minimal settlement. Shallow foundations for heavier stone structures may settle more heavily or in clay soil as in our case study. Settlement that occurs at different rates between different areas of a historic building is called differential settlement.

Accurate analysis for total and differential settlement requires detailed analysis and often involves innovative geotechnical engineering solutions, such as pile reduction settlement or preloading to reduce or control long-term ground movement. The site investigations involving complex FEM settlement analysis had been carried out.

Some of common factors that can contribute to the differential settlement under historic buildings are the weight, height of the stone walls, and primary and secondary compression of the fill and the natural soil. In addition to the construction method and construction details.

Designing foundations over soft soil is a difficult problem for geotechnical engineers due to undesirable settlement and bearing capacity performance. Many ground improvement techniques are used to overcome the difficulties associated with the high compaction and low shear strength of soft soils, [5]. Soft Clay soils are defined as saturated soils with low values for shear strength and modulus of texture, and also have high values for compaction, secondary stress, and long term creep deformation.

Advances in computer power have made numerical analyzes of complex problems in geotechnical engineering a popular approach. Researchers have adopted various simplified numerical models to predict the performance of soft clay soils and optimization techniques such as stone columns, unit cell model, homogenization method, plane stress technique, axial symmetry technique, and the full 3D model, [6, 7].

Simple Settlement Calculation:

$S = mv^*H^*\Delta\sigma$.

S = Settlement value.

mv = Soil compressibility, $m^2/MN = 1/E$.

$\Delta\sigma$ = Added soil pressure, kN/m^2

Settlement will take place when the applied pressure is higher than γz.

Structural deficiency and damage to built heritage or masonry structures is often the result of subsoil displacement, differential settlement or rotation of its foundations, or other negative effect of soil-structure interaction. Although it is necessary to study both the primary shear strength and the secondary and primary settlements of any historic structure, the research makes very limited contributions to the development of a numerical method to evaluate and classify the consequences of differential settlements on historic building, [8, 9]. In many cases, the settlement criteria will control what is allowed Endurance, [10, 11].

Due to recent advances in codes and programs for mathematical computing, numerical analysis has become a standard approach for exploring complex geotechnical issues. However, the corresponding physical and mechanical parameters are becoming more challenging.

On the one hand, satisfactory results for the numerical investigation of complex geotechnical issues can be obtained only by producing a robust three-dimensional numerical model like PLAXIS 3D; On the other hand, the behavior of soft saturated clay soils, collapsing and problematic soils subjected to fuzzy compaction methods must be predicted through the use of appropriate advanced constitutive models [12, 13].

The commercial package PLAXIS 3D (PLAXIS v.b, 2018) [14] was used for computational stresses and normalizations. It is limited-component software produced for geotechnical construction plan and inquiries and has recently been used as part of an examination of geostructures, [15].

Geotechnical and structural problems of Yashbak Palace (problem description)

Masonry load bearing walls of Yashbak palace may be classified as masonry cavity walls (multiple leaf walls), according to how they are constructed. In addition they are non-reinforced which cannot carry high stresses in particularly the shear stresses due to earthquakes or severe seismic events. Sometimes buildings, up to 16 storeys in height, have been built with non-reinforced masonry. In contrast, concrete reinforced walls or structures are reinforced with vertical and horizontal steel reinforcements but are less thick.

Yashbak Palace in Cairo was exposed to severe damage to the stone walls at both low and high levels due to geophysical factors, the most important of which was the 1992 AD earthquake, in addition to the rise in ground water levels (G.W.T) as well as long-term ancient flooding, which led to the entire walls being penetrated by cracks resulting mainly from ancient consolidation settlements, also the corner stones displaced in specific locations.

The main geotechnical problems and structural deficiencies of the vertical component of the structural system of Qasr Yashbak are: (I) the superstructure of the palace experienced severe damage and failure due to large-scale cracks associated with subsidence of load-bearing soil and foundation movements that experienced shear failure associated with major collapses. (II) partial collapse of the min façade of the palace. (III) the structural cracks are 2–7 cm wide and show periodic widening. The large cracks had a preferential orientation in two main directions, E-W and S-N, which includes typical views of the main cracks in the building facade and walls.

These structural deficiencies are due to damage caused by earthquakes, permanent deformations, significant subsidence of load-bearing soil, natural erosion of building materials, and the history of the complex's construction.

It seems that the causes of the structural damage such as collapses, cracks and displacements of the stone blocks and construction material decay are three of the problems that the palace suffers from which are mainly physical actions: (I) The difference in soil settlement due to consolidation and primary settlements, (II) The secondary settlement due to the reduction of the bearing capacity of the soil and the weak geotechnical properties of the soft clay soil and the rise of the groundwater level (G.W.T). (III) During the 700 years of its history as the destruction and displacements caused by earthquakes. The past seismic activities in particular Dahshuor earthquake 1992 AD, and (c) material decay and decreasing of the construction material strength due to the physiochemical and biological actions, where humidity often plays a prominent role due to high water levels for a long period of time. Many aspects of the structural deficiency and instability have been observed like the partial collapse of the main facade of Palace. In-plane and out-of plane deformation patterns like structural cracks and displacements, where the deformations appear inside and outside the main entrance level as shown in Figs. 1, 2, 3, 4.

According to historical facts the powerful earthquakes that have stuck the palace caused severe structural damages to the structural elements of the palace.

In the future: The strong mechanical strains to the palace are expected to be seismic, since we certainly hope that there will no longer be damage inflicted by mankind.

Imperative to evaluate the efficiency of the palace in seismic activity, taking into account the damage they have suffered through their long history.

Structural damages to the palace: Cracks, displacements, shifts, and failure of structural and architectural elements. The recognition of the structural damages on the palace due to seismic events from these caused by other reasons is a complex process with a compound content: historical, archaeological and technical.

Fig. 1 **a**. General view defines the location of Qasr Yahbak in Cairo. **b**. Collapsing of the middle part of the main façade of Qasr Yashbak

During the technical evaluation, almost all masonry walls showed a general case of off-plan shear and failure; this aspect, along with the presence of a large amount of priceless archaeological exhibits in the building, prompted the owner to start rehabilitation work.

The technical assessment revealed that almost all of the structural walls built at the all levels showed a fragile state of failure, and that from the first level to the roof level they were of the “weak and soft stories” type.

Advanced constitutive modeling

Structural analysis of historical masonry structures differs from the analysis and calculations made for new structures and the reasons mentioned above make it difficult to analyze these heritage buildings structurally. In these structures, uncertainties about the physical and mechanical properties of materials such as stone, brick, and joining mortar that form the carrier system also reduce the reliability of the results of the analysis. In order to determine the load-bearing system behavior of heritage buildings, many criteria such as the geometric form of the building, the materials used and the loads affecting the structure, and the foundation medium and geotechnical conditions should be considered.

There are two approaches to structural analysis and geotechnical modeling of the historic colossal stone/brick masonry structures: micro modeling and macro modeling. In the micro modeling technique, mortar used as binder and stone or brick material are modeled separately, while in macro modeling like in our case study, the materials are modeled as a single material, not separately. It makes this kind of micro analysis is very complicated in PLAXIS 3D and cannot make the geometry model directly without importing of CAD data. Also in the micro modeling approach, the stresses and load flow that lead to a decrease in stiffness can be observed. Since the mortar in the joints is weaker than the masonry units, the micro modeling technique, which is a method that focuses on the joints, is a method preferred for the detailed analysis of a part of the structures or structures that are not large and it is very difficult in the case of colossal masonry structures. In the micro modeling method, since the mechanical properties of the mortars and other construction materials like stones and bricks need to be fully known, a detailed material study is required before modeling.

PLAXIS Code uses predefined structural elements and loading types in a CAD-like environment. This empowers the user with the fast and efficient model creation, allowing more time to interpret the results. The user-friendly interface guides the user the efficiency create model with the logical geotechnical workflow in cont. The versatile output programme offers various ways to display forces,

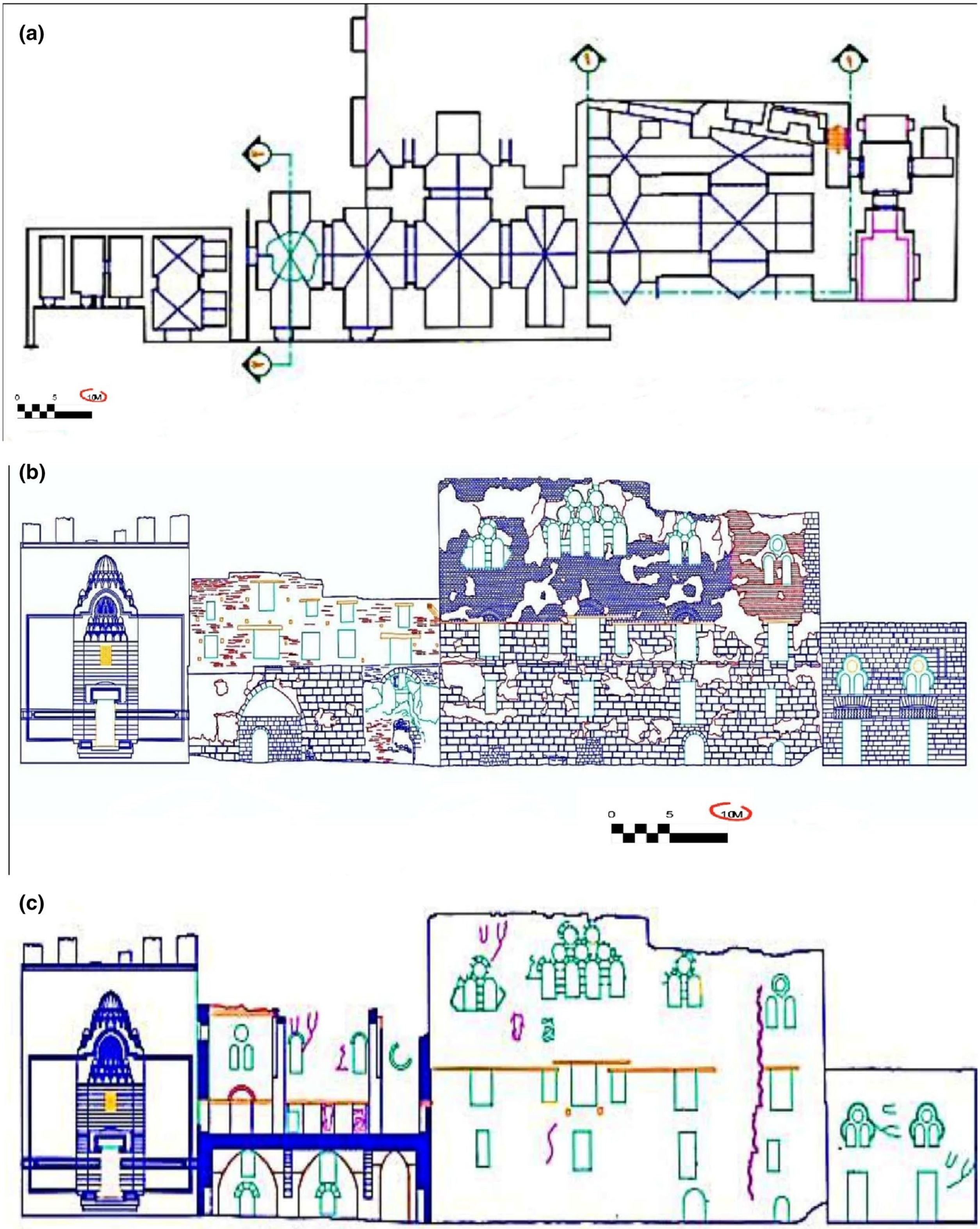

Fig. 2 **a**. The plan and layout of Qasr Yahbak, **b**. The elevation of the main façade of the palace. **c**. the degradation map of the main façade with the locations of structural cracks and other out of plane deformation patterns

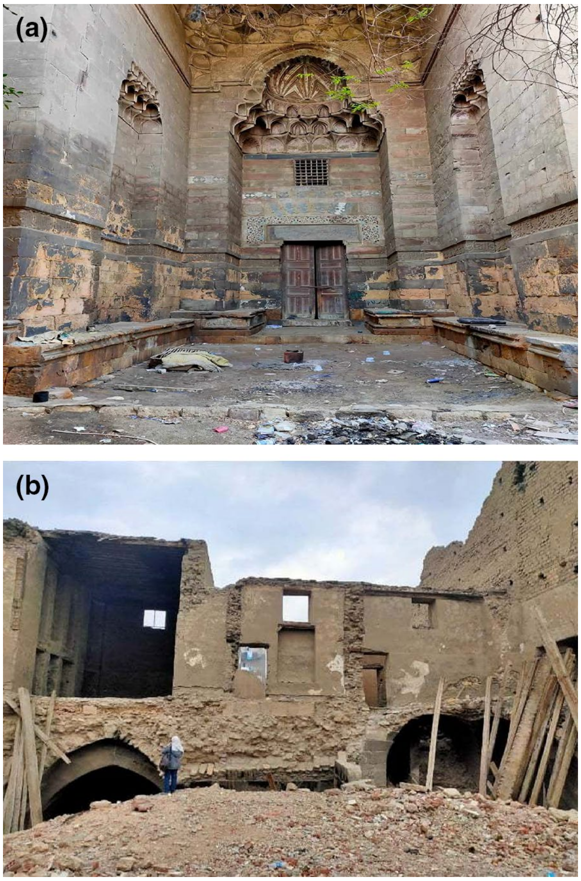

Fig. 3 Soil settlement of the bearing soil underneath the structure of the main entrance and b. The location of the collapsing part of the main façade of the palace due to 1992 earthquake and soil settlement

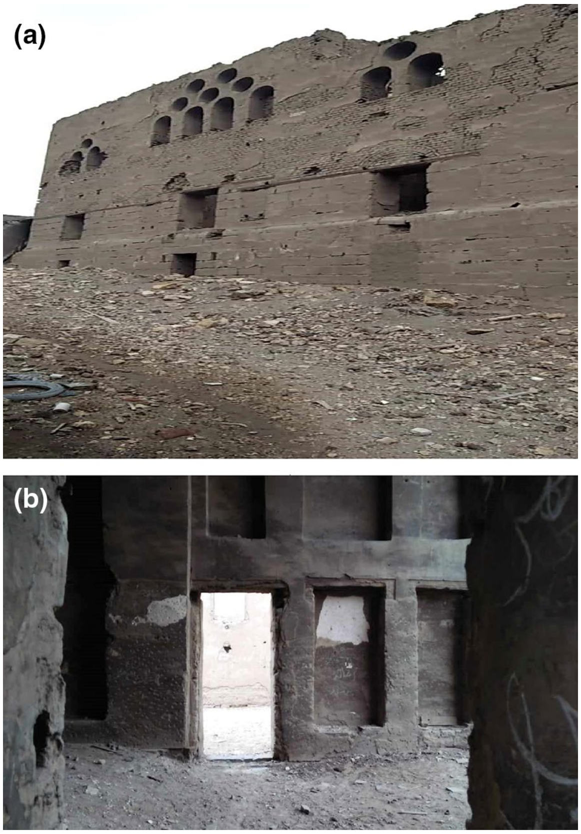

Fig. 4 **a**. In and out of plane deformations and distortions of the main façade are obvious. **b**. the state of preservation of the internal walls of the palace, the high raising of G.W.T and soiling of the stone walls is obvious

displacements, stresses and flow data in contour, vector and copied from tables or via python based scripting for further processing purposes outside of PLAXIS. The curve manager enables graph creation, plotting various results type from available calculation data.

PLAXIS 3D (used program in this study)

PLAXIS is an easy-to-use, finite element software application that helps with the analysis of subsurface environments for geo-engineering problems like our present analysis of soil problems under the colossal stone masonry structures.

PLAXIS offers extensive modeling features to model structures and the interaction between the structures and the bearing soil.

In the present study macro geotechnical and structural modeling done by importing the CAD data to PLAXIS 3D where PLAXIS 3D provides a large choice of structural elements: Anchors, Beams and embedded beams, Plates, Geogrids, and Interfaces. Plates have been used to represent the historic masonry structure in the present study.

Plates in PLAXIS are also offered in both 2D and 3D modeling environments and are formulated based on the Mindlin-Reissner theory. Equilibrium equations of the plate introduce: In-plane normal forces (2 components), Bending and twisting moments (2 + 1 components respectively), and Transverse shear forces (2 components).

Plates have been used for a large variety of masonry structures, including building floors and walls.

By introducing an interface along a line (or a surface in 3D), node pairs are created at the interface between the soil and the structure (one node belonging to the structure and the other one belonging to the soil).

Structural elements use normal forces, shear forces, and moments as primary variables to enforce equilibrium. As such, these structural elements are directly computed by the calculation kernel and reported into the post-processing environment (PLAXIS Output). This is convenient from a structural engineering point of view for the design and dimensioning of cross sections and elements thicknesses.

The accuracy of the structural element response is primarily related to its slenderness ratio. The idealization of its kinematics in a given direction(s) requires some structural dimensions (thickness for plates) to be small compared to other dimensions, enabling the simplification of their geometrical representation (to a surface for plates), [16].

Procedure used for simulation and analysis included:

- Create plate elements with help of 15 nodal points. 15-noded triangular isoperimetric elements are used to discretize the soil medium under the plane strain condition.
- Select plate command for the construction of the palace elements (Walls and Roofs).
- Select geometry line command and define various soil layers.
- Assign materials data to respective soil and structural elements.
- Generate and refine mesh (2D and 3D meshes).
- Define the ground water level and define phase.
- Generation of active pore pressure.
- Apply initial conditions and update calculations.
- Output calculations and analysis results.
- Creation of the next model.

PLAXIS code limitations

The PLAXIS code and its soil models have been developed to perform calculations of realistic geotechnical problems. In this respect PLAXIS can be considered as a geotechnical simulation tool. The soil models can be regarded as a qualitative representation of soil behaviour whereas the model parameters are used to quantify the soil behaviour.

Although much care has been taken for the development of the PLAXIS code and its soil models, the simulation of reality remains an approximation, which implicitly involves some inevitable numerical and modeling errors. Moreover, the accuracy at which reality is approximated depends highly on the expertise of the user regarding the modeling of the soil problem, the understanding of the soil models and their limitations, the selection of model parameters, and the ability to judge the reliability of the computational results. Both the soil models and the PLAXIS code are constantly being improved such that each new version is an update of the previous ones. There are limitations in all kinds of models of PLAXIS as shown in its manual as written in details in reference [17].

No doubt that using different coupling software such as the Finite Difference Method – Discrete Element Method should be able to find more accurate results for the structure modeling as compared to PLAXIS 3D in the current study and similar cases.

Characterization and engineering properties of the construction materials

The results of mechanical testing of the limestone specimens indicated that the design compressive strength of stone masonry $\sigma_c = 9.5$ MPa. The Modulus of elasticity $E = 6.5$ GPa. The Poisson ratio $\nu = 0.25$. The Shear strength $\tau = 4.5$ MPa. Tensile strength $\sigma_t = 1.2$ MPa. The cohesion $(c) = 950$ kN/m^2, the internal friction angle $\phi = 37$ degrees. Dry unit weight $\gamma_{unsat} = 20$ kN/m^3 and saturated unit weight $\gamma_{sat} = 22$ kN/m^3.

For the Brick masonry: the design compressive strength of masonry $\sigma_c = 13$ MPa. Tensile strength parallel to the bed joints $\sigma_t = 2.1$ MPa. Tensile strength perpendicular to the bed joints $\sigma_t = 1.2$ MPa. Shear strength $\tau = 5.5$ MPa. Modulus of elasticity $E = 12$ GPa. Poisson's ratio: $\nu = 0.20$. The cohesion $(c) = 1200$ kN/m^2, the internal friction angle $\phi = 30$ degrees. Dry unit weight $\gamma_{unsat} = 18$ kN/m^3 and saturated unit weight $\gamma_{sat} = 20$ kN/m^3. The engineering properties of the construction materials of Qasr Yashbak are summarized in Table 1.

Geotechnical conditions

Geotechnical properties

The subsoil of Qasr Yashbak consists of fine, saturated soft clay layers mixed with varying proportions of sand. Soft clay layers with a thickness of 4–10 m appear at a depth of 4.5 m below the ground floor level, where the first layers are backfilled (clay with stone fragments and crushed bricks of different sizes). The thickness of the backfill layers is from 3 to 4.5 m

Table 1 The Engineering properties of the building and construction materials of Qasr Yashbak

Building materials	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	σ_c (MPa)	σ_t (MPa)	E (GPa)	τ (MPa)	c (MPa)	φ (o)	ν (-)
Limestone	20	22	9.5	1.2	6.5	4.5	950	37	0.25
Bricks	18	20	13	2.1	12	5.5	1200	30	0.20

γ_{unsat} = Dry Unit Weight, γ_{sat} = Saturated Unit Weight, σ_c = Uniaxial compressive strength, σ_t = Brazilian tensile strength, τ = Shear strength, Vp = primary wave velocity, E = static Young's modulus, Edy = Dynamic Young's modulus, ν Poisson's ratio, G = Shear modulus. c cohesion, φ internal friction angle

Table 2 The physical and mechanical properties of soil layers underneath Qasr Yashbak

Soil type	Liquid limit (WL) %	Shrinkage limit (WS) %	Plasticity limit (WP) %	Dry unit weight ($\gamma_{unsat)}$	Saturated unit weight ($\gamma_{sat)}$	Specific gravity (Gs)	Permeability $K_x = k_y$ (m/day)	Initial void ration (e)	Compression index Cc	Young's modulus E kN/m^2	Poisson's ratio	E_{oed} kN/m^2	Soil cohesion (c) kN/m^2	Friction angle (φ) o
Clay	110	18.5	48.4	18–19	20	2.7	$1.58*10^{-4}$	0.7338	0.2316	2000	0.4	1204	65	30
Fill	–	–	–	15	16–17	–	–	–	–	1000	0.3	–	–	–

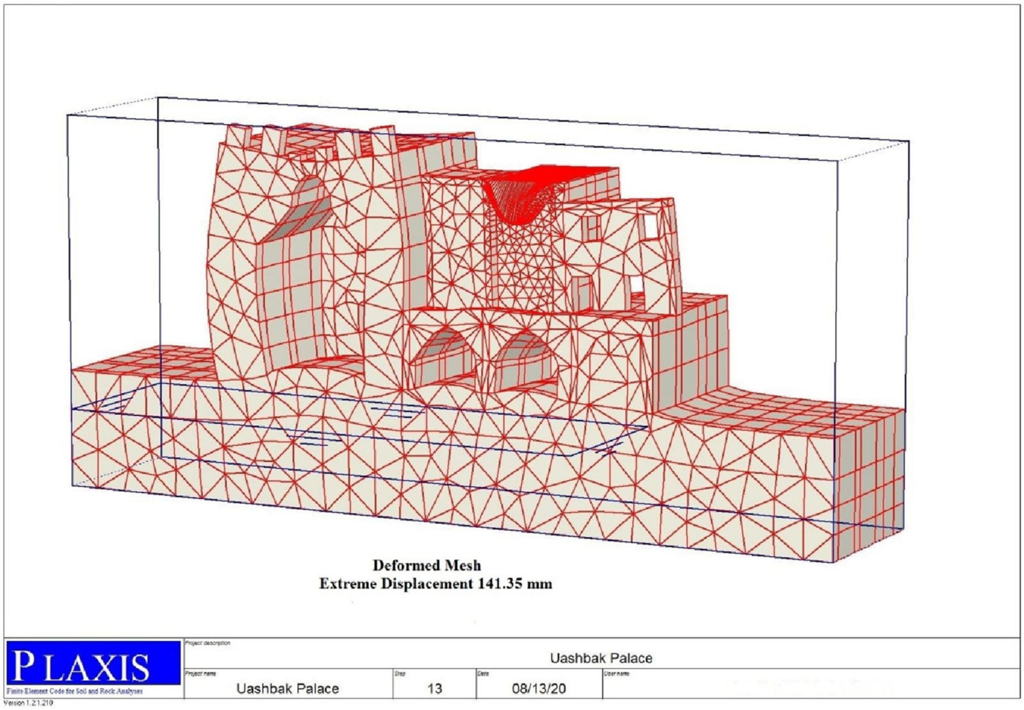

Fig. 5 Three Dimension Finite Elements discretization of the PLAXIS model and deformed generated mesh

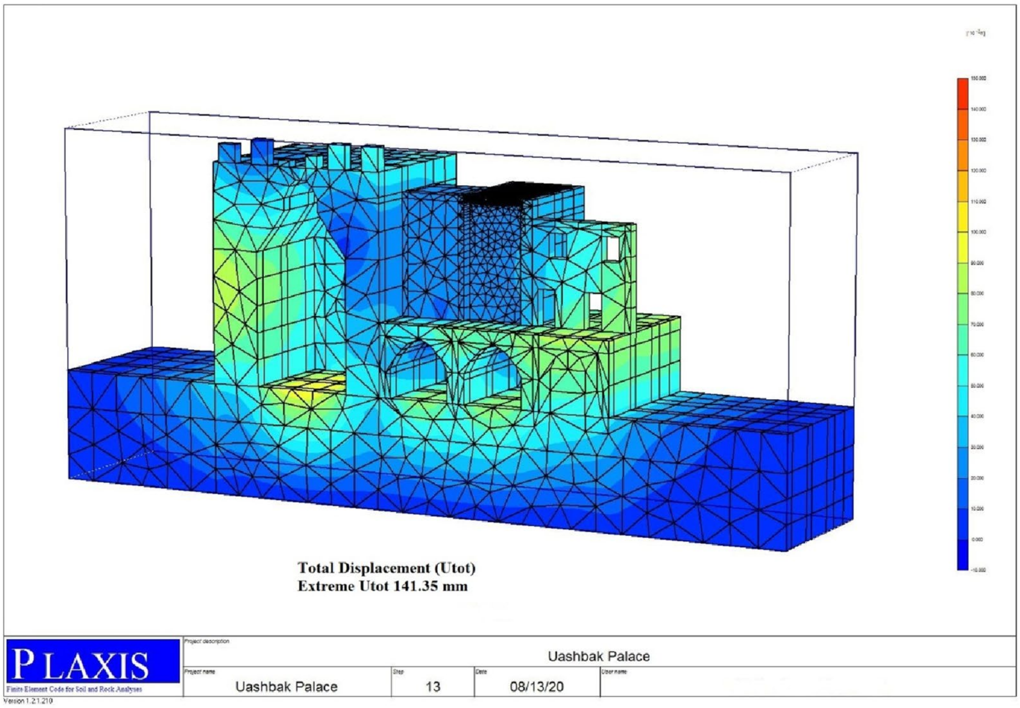

Fig. 6 Total displacement developed at the surface, right above reached a maximum value of about 141.35 mm which is the total consolidation settlement and local shear failure of the bearing soil due to the in-plane loading

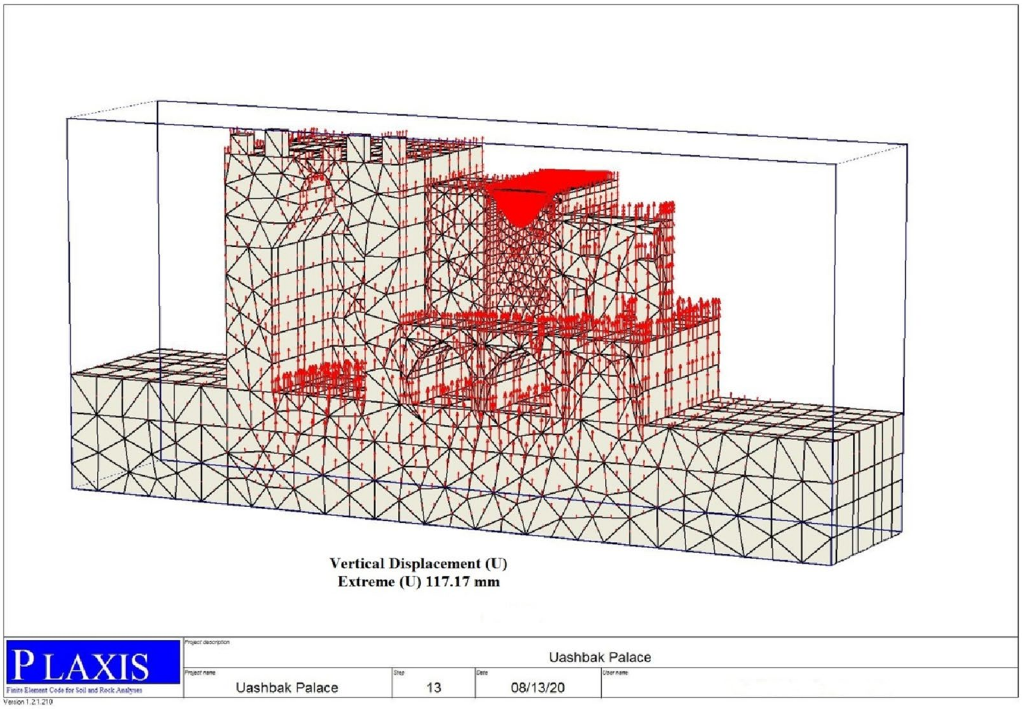

Fig. 7 Deformed mesh and the calculated vertical displacements of the bearing soft clay saturated soil and its distribution underneath the superstructure of the palace (Uy) is 117.17 mm

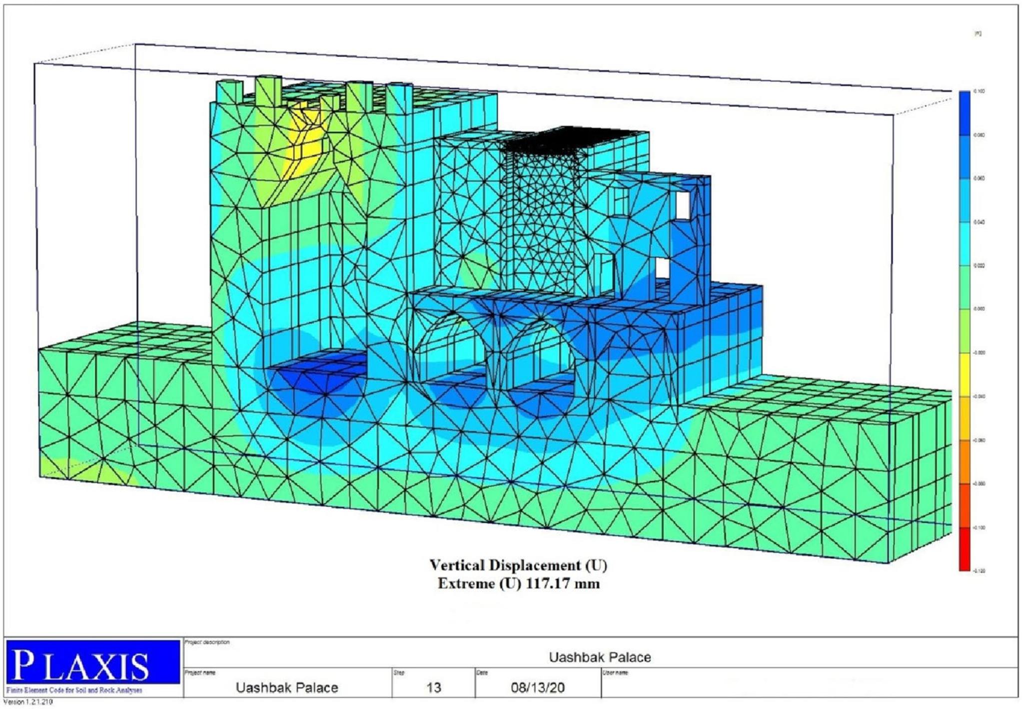

Fig. 8 Deformed mesh and the calculated vertical displacements of the bearing soft clay saturated soil and its distribution underneath the superstructure of the palace (Uy) is 117.17 mm

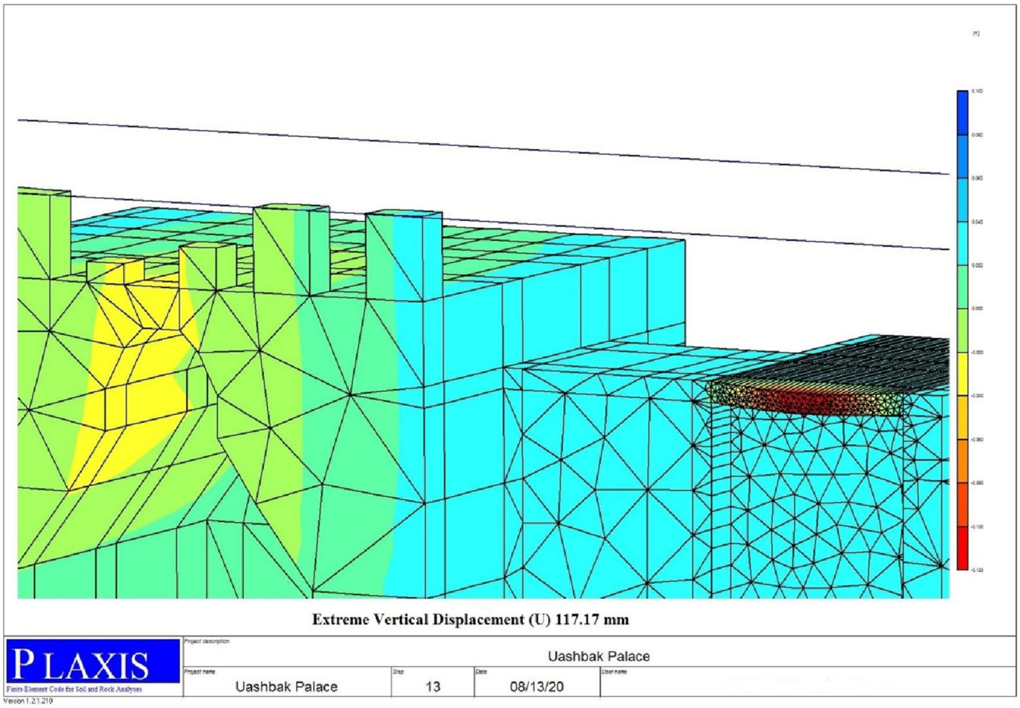

Fig. 9 Calculated vertical displacements of the super structure of Qasr Yashbak due to the bearing soil primary and secondary settlement

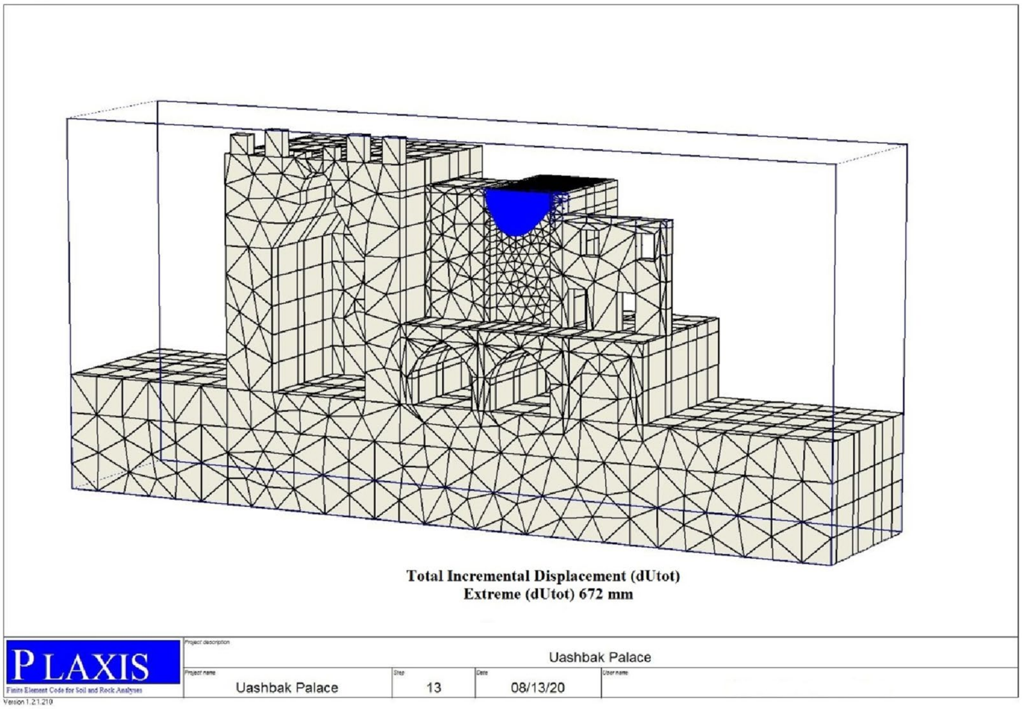

Fig. 10 Total incremental displacement (dUtot) patterns in the bearing silty clay soil where the extreme (dUtot) is 672 mm

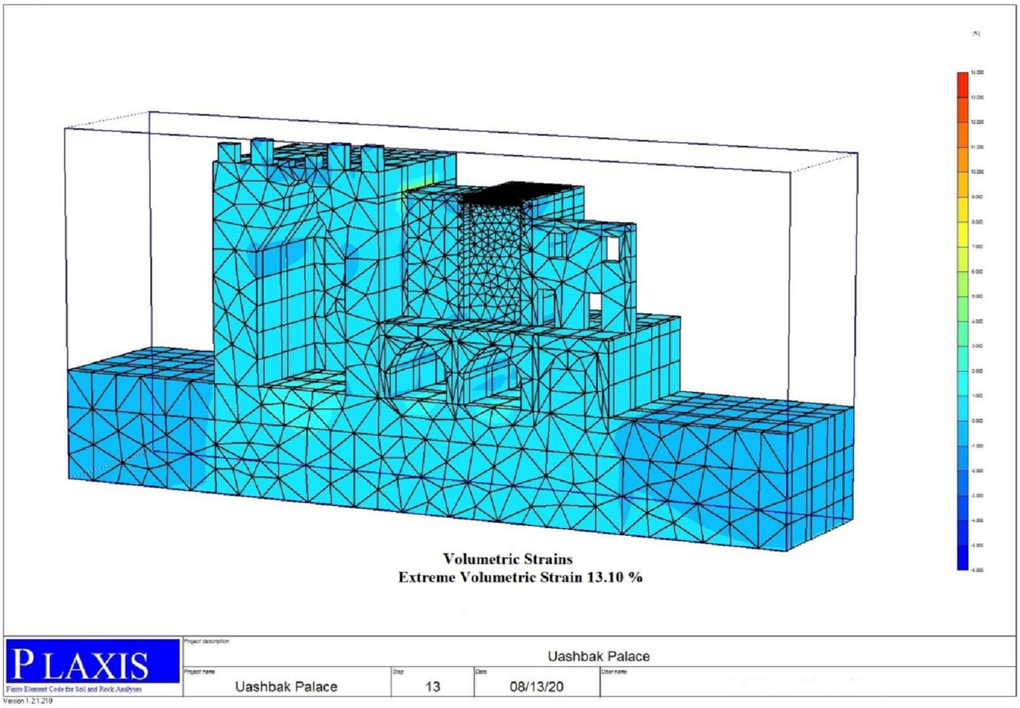

Fig. 11 Distribution of the volumetric strain of the soil was calculated where the extreme value is 13.10%

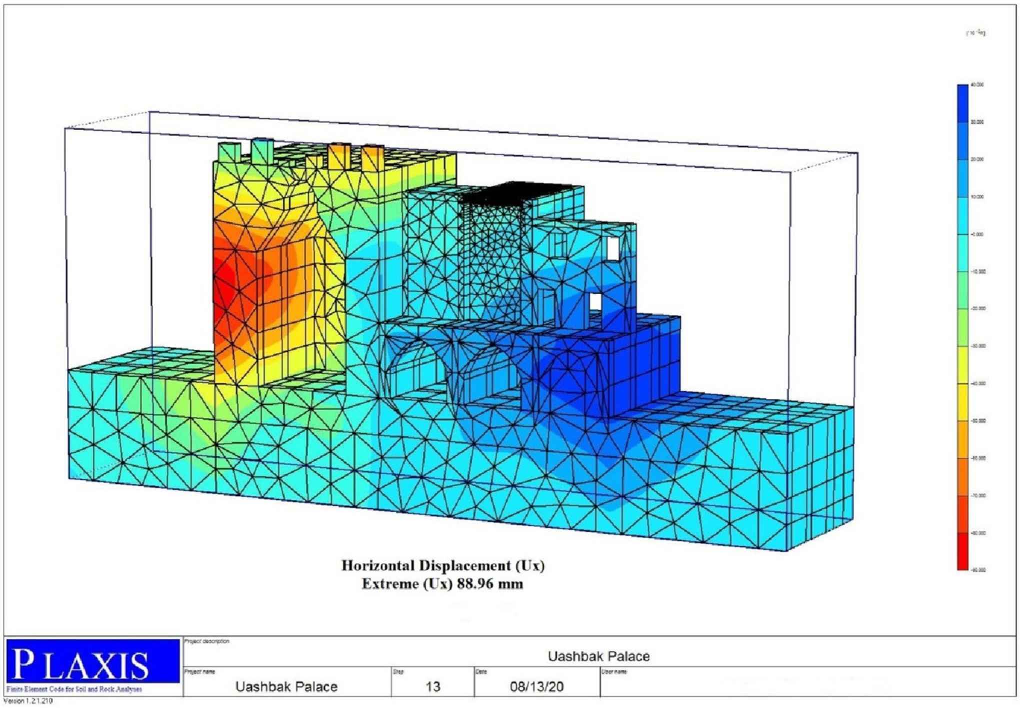

Fig. 12 Extreme horizontal displacement (Ux) of the main entrance due to the bearing soil settlement is 88.96 mm

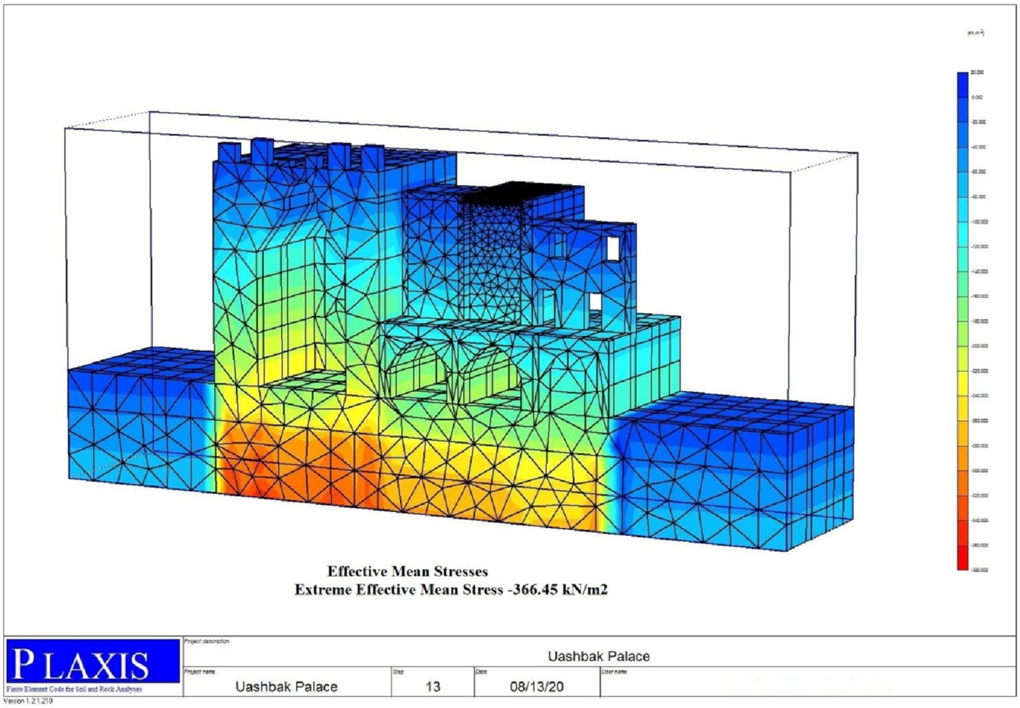

Fig. 13 Extreme effective mean stresses in the bearing soil underneath the main entrance is 366.45 kN/m^2

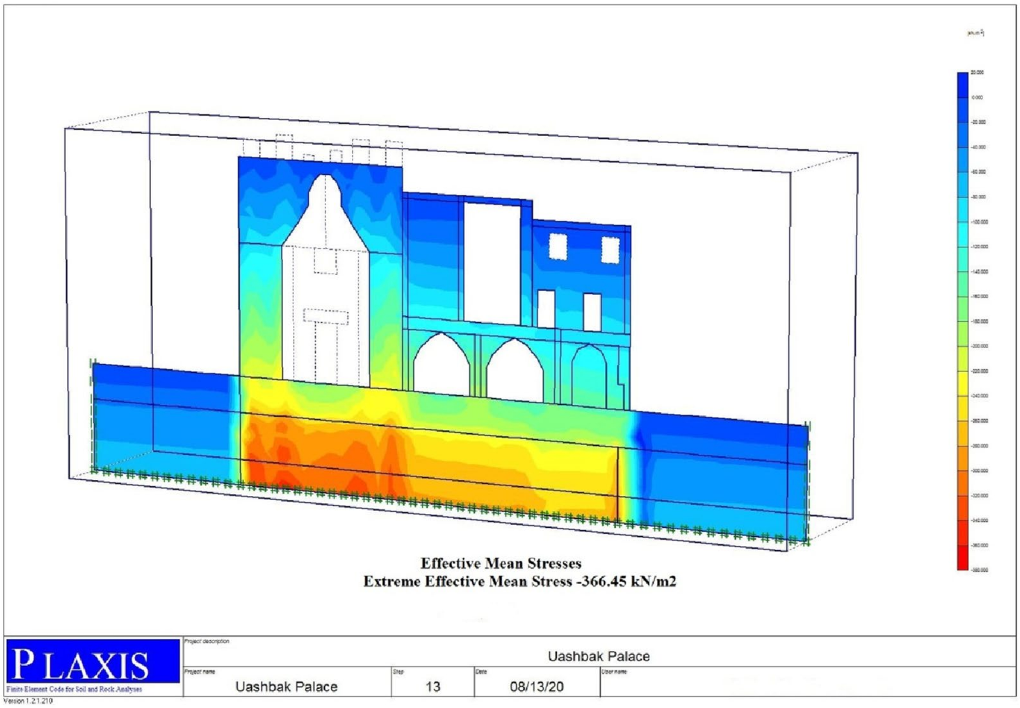

Fig. 14 Distribution effective mean stresses in the bearing soil underneath the main entrance

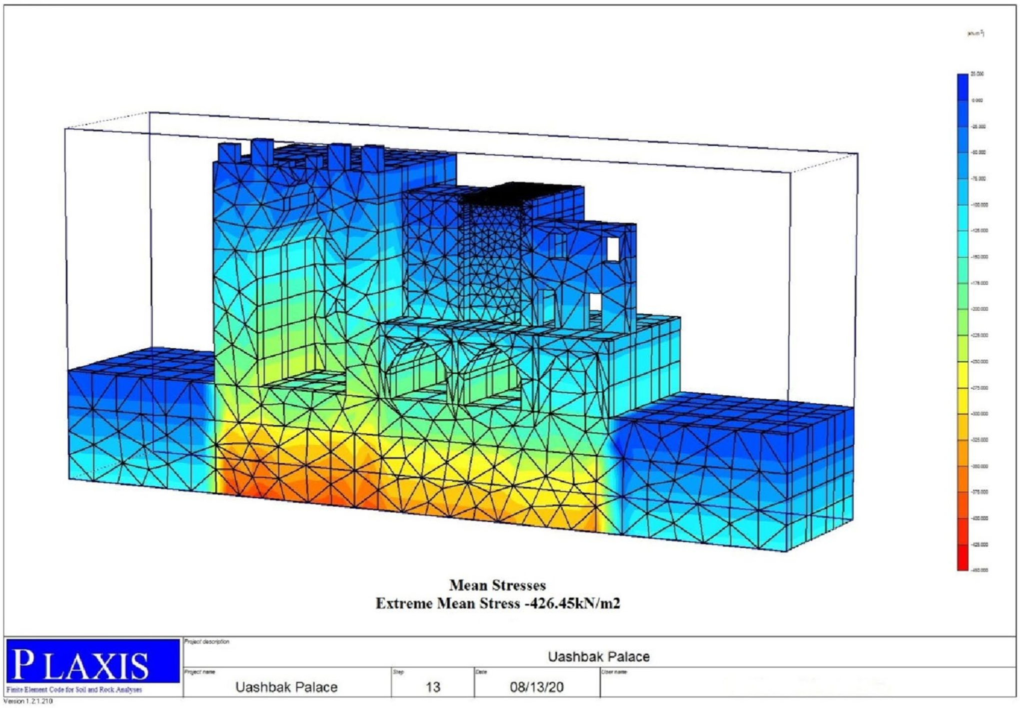

Fig. 15 Extreme mean stress in bearing soil underneath the main entrance is 426.45 kN/m^2

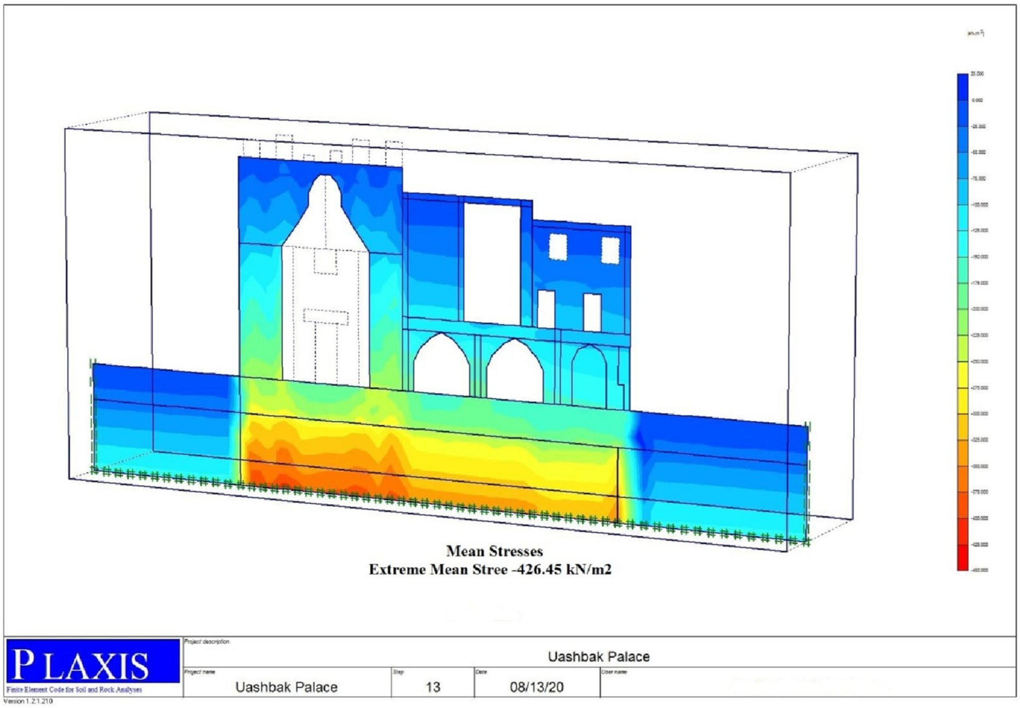

Fig. 16 Distribution of mean stress in bearing soil underneath the main entrance of Qasr Yashbak

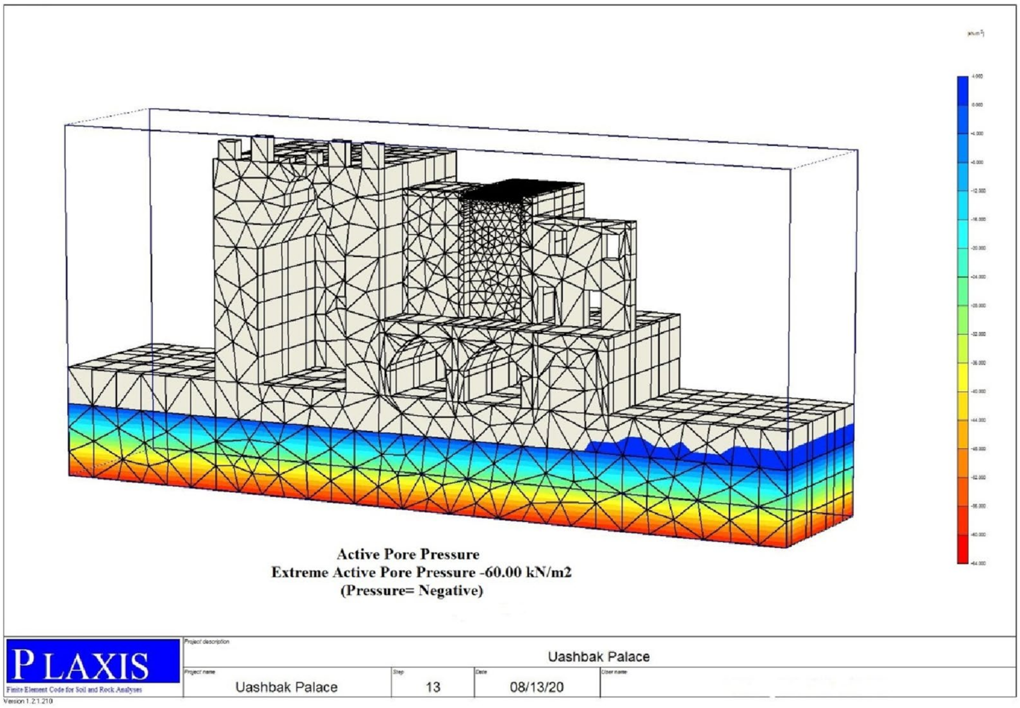

Fig. 17 Distribution of the active pore pressure P_{active} in the subsoil, where the extreme value reached–60 kN/m^2

with a dry unit weight $\gamma = 15$ kN/m^3. The groundwater level appears at a depth of 1.8 m. Table 2 summarizes the geotechnical characteristics of the soil layers below Qasr Yashbak. For clay layers: liquid limit (WL) = 110, shrinkage limit (WS) = 18, plasticity limit (Wp) = 48, dry unit weight = 18–19 kN/m^3, saturated unit weight = 19–20 kN/m^3, specific gravity GS = 2.7, initial void ratio ei = 0.7338, final void ratio $e_f = 0.334$. Compressive coefficient of compression coefficient Cc = 0.2316. Young's modulus E = 2000 kN/m^2, Poisson's ratio $\upsilon = 0.4$, cohesion (c) = 65 kN/m^2, friction angle $\phi = 30$ degrees. Test setup was carried out in the soil mechanics laboratory in the civil engineering department of the University of Business and Technology (UBT) in Jeddah, Saudi Arabia.

The Log vertical stresses kPa (log σv) Vs the vertical strain (εv) was obtained through the consolidation test. Where the minimum values are ($\varepsilon = 0.0075$ associated with $\sigma = 17.07$ kPa) and the maximum are ($\varepsilon = 0.0596$ associated with $\sigma = 2814$ kPa).

The Log vertical stresses kPa (log σv) Vs the Void ratio (e) also obtained. Where the initial Void ratio is ($e_0 = 0.7338$) and the final Void ratio is ($e_f = 0.334$). The pre-consolidation stress Pc is 480 kPa and the compression Index Cc is 0.2316.

Log vertical stresses kPa (log σv) Vs the Modulus of Compression (E) calculated, where the minimum values are ($\sigma v = 17.07$ and E = 2276.14 kPa) and the maximum are ($\sigma v = 2814$ and E = 47214.7 kPa).

Log vertical stresses kPa (log σv) Vs the Coefficient of Consolidation (Cv) (m^2/sec) obtained, where the Cv is 0.0001021 m^2/sec when vertical stresses σv is 18.38 kPa.

Consolidation Settlement calculations for the soft saturated clay layers determined from the empirical study give the same settlement value, Eq. 1;

Soil samples was obtained from the clay layer, consolidation test, (9 load increments, in the lab the stresses are added to the soil sample and during testing, the geostatic stress is gradually recovered) had been conducted, void ratio (e) vs. pressure log (p) plotted and the Compression Index (Cc) & Swelling Index (Cs) had been determined.

$$\Delta H = \frac{Cc \text{ x } H}{1 + e_O} \log \left(\frac{P_O + \Delta P}{P_O} \right) \tag{1}$$

ΔH is the consolidation adjustment, Cc is the compression index, H is the height of the saturated Clay soil layer is 10 m, (e_0) is the initial Void ratio, (P_0) is the initial effective vertical stress in the middle of the mud layer depth, ΔP is the change in the vertical effective stress (weight of the building).

ΔH is the consolidation settlement of the soft saturated clay layer = (0.232 × 10)/(1 + 0.7338) x (log (150 kN/m^2 + 38 kN/m^2)/150 kN/m^2) = 131 mm.

Fig. 18 Details of the induced vertical displacement of the super structure and bearing soil of Qasr Yashbak due to the primary and secondary consolidation settlement

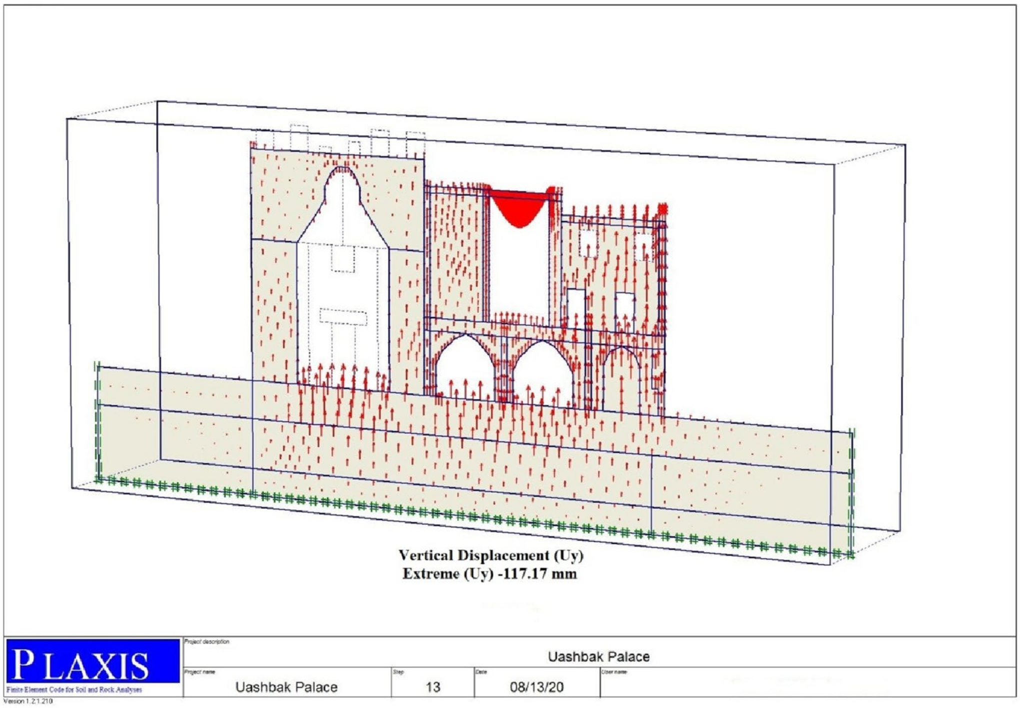

Fig. 19 Details of the induced vertical displacement of the super structure and bearing soil of Qasr Yashbak due to the primary and secondary consolidation settlement

Where the thickness of layer H is 10 m, the compression index Cc = 0.232, the initial stress in the middle depth of the clay layer is $P_0 = (4\ m \times 15\ kN/m^3 + 5\ m \times 18\ kN/m^3) = 150\ kN/m^3$. The initial void ratio is 0.7338.

Ground water table

Ground water table encountered at each geotechnical borehole during drilling. The ground water table fluctuated from 2 to 2.5 m below ground surface. Water table measured in borehole should not necessarily be considered to represent stabilized ground water levels, because the water levels are expected to fluctuate seasonally.

Numerical analysis results and discussions

A PLAXIS three-dimensional finite element model was generated, using commercial finite element software program PLAXIS 3D, to perform long-term soil-structure settlement analysis. The developed finite element model consists of an approach stone masonry structure, fill, and natural clay soil.

The results of the numerical analysis of Qasr Yashbak as it was originally designed show that some surface subsidence occurred during construction on thick (7 m) smooth mud layers. Figure 5 presents the 3D finite element partitioning of the PLAXIS model and the generated deformable network. The total displacement value developed at the surface top right had a maximum value of about 141.35 mm which is the total cohesion settlement and local shear failure of the load-bearing soil due to in-plane loading, as shown in Fig. 6.

Figures 7, 8, 9 show the deformed network and the calculated vertical displacements of the soil saturated with loose clay and its distribution under the superstructure of the palace Uy, which is 117.17 mm.

Figure 10 presents the patterns of total incremental displacement (dUtot) in silty-bearing clay soil where the maximum (dUtot) is 672 mm. The distribution of the volumetric strain of the soil was calculated, where the extreme value is 13.10% as show in Fig. 11. The extreme horizontal displacement (Ux) of the main entrance due to the bearing soil settlement is 88.96 mm as shown in Fig. 12. The extreme effective mean stresses in the bearing soil underneath the main entrance is $366.45\ kN/m^2$, as shown in Figs. 13 and 14. The Extreme mean stress in bearing soil underneath the main entrance is $426.45\ kN/m^2$, as shown in Figs. 15 and 16. Figure 17 represents the distribution of the active pore pressure P_{active} in the subsoil, where the extreme value reached $60\ kN/m^2$. It is obvious that the he mean stresses ($426.45\ kN/m^2$) equal effective stresses ($366.45\ kN/m^2$) plus the active pore pressure P_{active} ($60\ kN/m^2$). The value of the initial vertical effective compressive stress at the mid depth of the clay layer has been determined, where $\sigma v = 350\ kN/m^2$. Figures 18 and 19 represents details of the induced vertical displacement of the super structure and bearing soil of Qasr Yashbak due to the primary and secondary consolidation settlement.

This numerical result confirms the occurrence of surface subsidence due to subterranean sedimentation, deformations and stress interactions observed in the superstructure of the palace. the subsidence of the bearing soil may crack the superstructure of the palace. The main reasons are uniformity. Also, the shear failure characteristics of the subsoil may lead to subsidence.

Thus, it can be concluded that modeling the behavior of soft clay soils under Qasr Yashbak by numerical analysis is suitable for understanding the studied behavior of this type of formed soil [18–25].

There is no doubt that the analytical results of the study can be generalized to any archaeological building in the similar geotechnical conditions anywhere in the world, as the research presents a new attempt to use a couple model to study this type of saturated clay soil problem and its impact on the structural integrity of the built heritage. This study represents how to analyze and estimate subsidence and settlement in an accurate numerical manner, and to know the extent of the impact of this subsidence on the structural safety of this building. Historic buildings have complex nature whose structural behavior is difficult to predict under changing of its geotechnical conditions. The study also presents a new idea to estimate the geo-environmental risks and how to protect this high valuable built heritage.

Conclusions

Consolidation of soft clay and the resulting stability issues under a monument has been paid much attention, with a very popular example of the Leaning Tower of Pisa, [30, 31]. Numerical model calibration was performed based on the in-situ measurement data to determine the corresponding model parameters. Various methods of parameter improvement were investigated. Thus, it can be concluded that modeling the behavior of soft clay soil under Qasr Yashbak by numerical analysis is appropriate to understand the studied behavior of this type of problematic soil. The results of geotechnical modeling and FEM deformation analysis showed that the impact of impermissible underground subsidence exceeding 14 cm is evident. the structural damage caused by soil differential settlement highlighted that the internal and external collapse of the facade and other stone walls is the main cause. The numerical results indicated that, the main method of failure in old stone buildings, especially due to ineffective contact with the floors, [28–31].

Overall, while the paper presents valuable insights into the behavior of soft clay soils under colossal stone/brick masonry structures, it lacks specific details about the limitations and potential sources of error in the research methodology. Further research and analysis may be required to address these limitations and enhance the understanding of the studied behavior.

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Declarations

Competing interests
The author declare that he has no competing interests.

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