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Vulnerability of Baghdad Soil to Liquefaction (Numerical Study)

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Keywords:
Baghdad's soil; Earthquake Hazard; liquefaction phenomenon; Pore water Pressure ratio; Seismic Iraq; Liquefaction vulnerability.

Highlights:

- *The potential liquefaction investigated Baghdad's soil using the PM4Sand constitutive model within the PLAXIS 2D framework.*
- *The research employed excess pore water pressure ratio (ru) as the primary indicator of liquefaction potential, along with the observation of significant deformations or loss of shear strength.*
- *The model was used to systematically study the impact of key parameters, such as relative density (DR), shear modulus (Go), contraction rate parameter (hpo), bounding surface parameter (nb), and critical state line parameter (R).*

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Abstract: A phenomenon known as "earthquake liquefaction" or "soil liquefaction" occurs when a mass of saturated soil gradually loses strength as a result of increased excess pore water pressure generated by ground shaking during a strong earthquake. In other words, the state condition of soil liquefaction is when the soil's effective stress momentarily drops to zero. Iraq's capital is Baghdad, located in a moderately seismically active area. The soil layers for Baghdad city bear silty, a shallow sand layer and the groundwater level exists. This study investigates if Baghdad soil may be liquefied by studying the factors on which the liquefaction phenomenon depends. The factors as relative density (D_R= 30, 50, 75 and 85 %), shear modulus (G_o= 35, 65, 85, 95 and 125) MPa, shrinkage rate coefficient (h_{po} from 0.1 to 8), surface modulus, (n^b from 0.2 to 5) and critical state line coefficient (R from 1.5 to 5) have been changed based on the Halabja earthquake. The study was analyzed by PLAXIS 2D, and the PM4Sand model was chosen for the liquefiable layer to evaluate the possibility of liquefaction and investigate the impact of the earthquake intensity and its duration on the occurrence of the liquefaction. The properties of the soil stratification were chosen from available data for 200 boreholes, and 630 tested samples were selected from all Baghdad regions, which normalized the physical and engineering properties data.

قابلية تربة بغداد للتميُّع (دراسة عددية)

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الخلاصة

تحدث ظاهرة تُعرف باسم "تمييع التربة" أو "سيولة التربة" عندما تفقد كتلة من التربة المشبعة قوتها تدريجياً نتيجة لزيادة ضغط الماء المسامي الزائد الناتج عن اهتزاز الأرض خلال زلزال قوي. وبعبارة أخرى، تكون حالة سيولة التربة عندما ينخفض الإجهاد الفعال للتربة إلى الصفر لحظياً. تقع العاصمة العراقية بغداد في منطقة ذات نشاط زلزالي متوسط. تحمل طبقات التربة في مدينة بغداد طابع التربة الطينية الغرينية، مع وجود طبقة رملية ضحلة، ويوجد مستوى للمياه الجوفية. تحقق هذه الدراسة في إمكانية حدوث تمييع لتربة بغداد من خلال دراسة العوامل التي تعتمد عليها الظاهرة. تم تغيير العوامل مثل الكثافة النسبية(DR = 30، ٥٠، ٧٥، و ٨٥٪)، ومعامل القص(G0 = 35، ٦٥، ٨٥، ٩٥، و ١٢٥ ميجا باسكال)، ومعامل معدل الانكماش (hp0) من ٠,١ إلى ٨)، ومعامل السطح (nb) من ٠,٢ إلى ٥)، ومعامل خط الحالة الحرجة (R) من ١,٥ إلى ٥ (استناداً إلى زلزال حلبجة. تم تحليل الدراسة باستخدام برنامجPLAXIS 2D ، وتم اختيار نموذج PM4Sand للطبقة القابلة للتمييع لتقييم إمكانية حدوث التمييع والتحقق من تأثير شدة الزلزال ومدة استمراره على حدوث الظاهرة. تم اختيار خصائص طبقات التربة من البيانات المتاحة لـ ٢٠٠ حفر جوي، وتم اختيار ٦٣٠ عينة مختبرة من جميع مناطق بغداد، مما أدى إلى توحيد بيانات الخصائص الفيزيائية والهندسية.

الكلمات الدالة: تربة بغداد، المخاطر الزلزالية، ظاهرة التمييع، نسبة ضغط الماء المسامي، الزلزالية في العراق، القابلية للتمييع.

1.INTRODUCTION

Liquefaction is a phenomenon in which saturated and cohesionless soil loses its strength due to higher pore water pressure build-up. However, the effective stresses will lessen as the space between individual particles is filled with water, which exerts pressure on the soil particles [1]. The cycle of earthquake ground motion and other dynamic vibrations reduces soil stiffness and strength. Liquefaction is the main factor responsible for the loss of life and property in earthquake-prone areas worldwide [2]. Numerous research studies have been conducted to assess Liquefaction triggering of soil by using considerable methods. Byrne et al. [3] investigated liquefaction occurrence by creating an efficient stress numerical modeling approach to evaluate the results of three centrifuge tests. Anwar et al. [4] used multi-linear regression modeling. The estimation of liquefaction progression by creating several 1D soil models using the object-oriented software OpenSees was carried out [2]. Later, [5] employed ambient noise, and [6] tested machine learning based on SPT data. Considerable studies have evaluated potential liquefaction by assessing the excess pore water pressure (r_u) [7]. The study conducted by Vilhar et al. [8] that described the implementation, validation, and application of the PM4Sand model (version 3)) in PLAXIS. Subasi et al. [9] used the PM4Sand constitutive model in the PLAXIS 2D finite element software to get potential liquefaction and induced settlement. Saikia and Chetia [10] studied many factors that affect liquefaction, such as soil types, Earthquake magnitude and period, etc. Based on the 2003 literature review, a total of 22 influential elements related to soil liquefaction were identified and summarized. After a statistical analysis using the ISM model, [11] found that 12 influential factors were identified. These factors included magnitude, epicentral distance, and duration of earthquake. Also, fines content, particle size, grain composition, relative density, drainage condition, degree of consolidation, sand layer thickness and depth, furthermore the groundwater table were involved. The ISM model demonstrated that the magnitude, epicentral distance, and duration of the earthquake directly influenced soil liquefaction. Among these characteristics, fine content and relative density were particularly crucial. Understanding seismology and liquefaction susceptibility is significant for urban areas owing to many compelling factors [12]. Examining seismology allows us to evaluate the possible consequences of seismic occurrences on the city's infrastructure, buildings, and population, therefore facilitating the creation of efficient measures to reduce their impact and improve resilience. Based on the U.S. Geological Survey data, no evidence suggests that the overall intensity of earthquakes worldwide is on the rise. Furthermore, the observed increase in earthquake occurrences can be attributed to the expanded deployment of seismic sensors, enabling a greater capacity to detect and record earthquakes rather than an actual increase in the occurrence of earthquakes. Human actions can impact seismic activity and potentially initiate earthquakes. Although these occurrences are often less potent than natural earthquakes, they can nonetheless have a substantial impact. Mining, dam construction, and hydraulic fracturing (fracking) have been linked to induced seismic activity. Baghdad is located in a zone prone to seismic activity, rendering it vulnerable to earthquakes. Furthermore, the susceptibility to liquefaction in Baghdad could be a critical issue, considering Baghdad's geological conditions and the location of the Tigris River. The risk of liquefaction consequences resulting in ground instability and the possibility of structural damage. Examining liquefaction susceptibility can identify regions with elevated risk, design suitable foundation systems for structures, and enforce land-use planning strategies to mitigate potential dangers. The current research desired to study the impact factors that affect the liquefaction phenomenon, such as soil relative density (D_R) and initial shear modulus (G_o). Also, the accuracy of soil modeling PM4Sand in PLAXIS, such as the soil contraction rate (h_{po}) under cyclic loading in constitutive models, bounding surface parameter (n^b) that characterized the nonlinear behavior of soils, and the critical state line parameter (R), was verified. Finally, it investigated the estimated liquefaction phenomenon, and it tested the possibility of liquefaction occurring in the soil of the Iraqi capital, Baghdad, when exposed to a real earthquake with a vigorous intensity, such as, the Halabja earthquake with a magnitude of 7.3 Ml in 2017. The effects of both the duration and seismic intensity on this phenomenon by employing Finite element (FE) analyses in PLAXIS 2D software were comprised as well.

2.METHODOLOGY

This study focuses on numerical modeling using PLAXIS 2D CONNECT Edition V21 (2022) to estimate the possibility of liquefaction occurrence. The PLAXIS 2D finite element software analyzes geotechnical engineering problems like deformation, stability, and water flow [13]. The improved output facilities of the input procedures make a thorough presentation of the computational results possible. For seismic engineering applications, Boulanger and Ziotopoulou [14] suggested the PM4Sand (version 3) constitutive model to represent sand. After this, several studies interested in soil liquefaction verified this model and achieved satisfactory results. Toloza [15] employed Liquefaction modeling using the PM4Sand Constitutive Model in PLAXIS 2D, and then Portugal [16] analyzed the liquefaction risks and evaluated the effectiveness of the model, including the presence of a simplified structure. The subsurface conditions of the suggested construction location were investigated using the parameters obtained from the investigated boreholes, which were implemented as pm4sand for sand and HS small model for clay layer as in PLAXIS 2D liquefiable soil. Two hundred borehole results and related data were gathered from various public and private organizations in Baghdad; references were made [17]. The locations of the sites were randomly distributed over Baghdad, and in certain cases, the depth of the soil layer varied from 8 to 46 meters. The spatial positions and distribution of site points in Baghdad city were displayed using ArcMapGIS10.3 approaches, as shown in Fig. 1. The data with the SPT values included the soil fraction, density, water content, liquid limit, plasticity index, and elevation of the water table. The parameters of the engineering and seismic soil layers at different depths were considered after a comprehensive normalization examination of the data. The Z-score normalization or Z-score standardization method [18] was utilized to develop a single relationship between the soil parameters for each specified depth. In this method, the parameters at quantified depth were averaged and standardization, then the normalized values at each depth, Z-scores were used, which will adjust the data based on the mean and standard deviation:

$$Z_d = \frac{Soil\ parametr - \mu_d}{\sigma_d} \quad (1)$$

where

Z_d : the normalized soil parameter value at depth d

μ_d: the mean soil parameter at depth d

σ_d: the standard deviation at depth d

It has been noticed that there are no observed fluctuations in the normalized parameters.

The results obtained from the normalization method revealed that the soil profile is composed of multiple layers, each with distinct properties. It includes a top clay layer of 1.6 m of drained clay and 3.4 m of undrained clay, a central silty sand layer 18.5 m thick, then a third layer of clay of 5.5 m, and finally, a bedrock layer of 1 m at the bottom, as shown in Fig. 2. The water table is located 1.6 meters below the ground surface. The acceleration history of Halabja was utilized as an input ground motion. Assuming that the earthquake would be measured at the outcrop of a rock formation, modeling the event required imposing a predetermined displacement at the model's base. The boundary condition for the model's base was determined using a compliant foundation. Tied degrees of freedom were used in the vertical border modeling. It is worth mentioning that the element was taken without overburden pressure. The dimensions were taken as follows [1]: x_{min}= 0.0 m, x_{max}=2.0 m, y_{min}= 0.0 m and y_{max}= 30.0 m. The undrained cyclic response of the PM4Sand constitutive model was developed using a finite element method with a licensed representation of PLAXIS 2D to simulate the liquefaction triggering of sand. The responses of the soil model change depending on the cyclic stress levels and test conditions used, considering that the soil column isn't subject to confining pressure. The mesh of the soil profile generated by PLAXIS 2D is shown in Fig. 3. The normalized soil parameters from the site data representing the first, second, and third layers are presented in Table 1, Table 2, and Table 3, respectively.

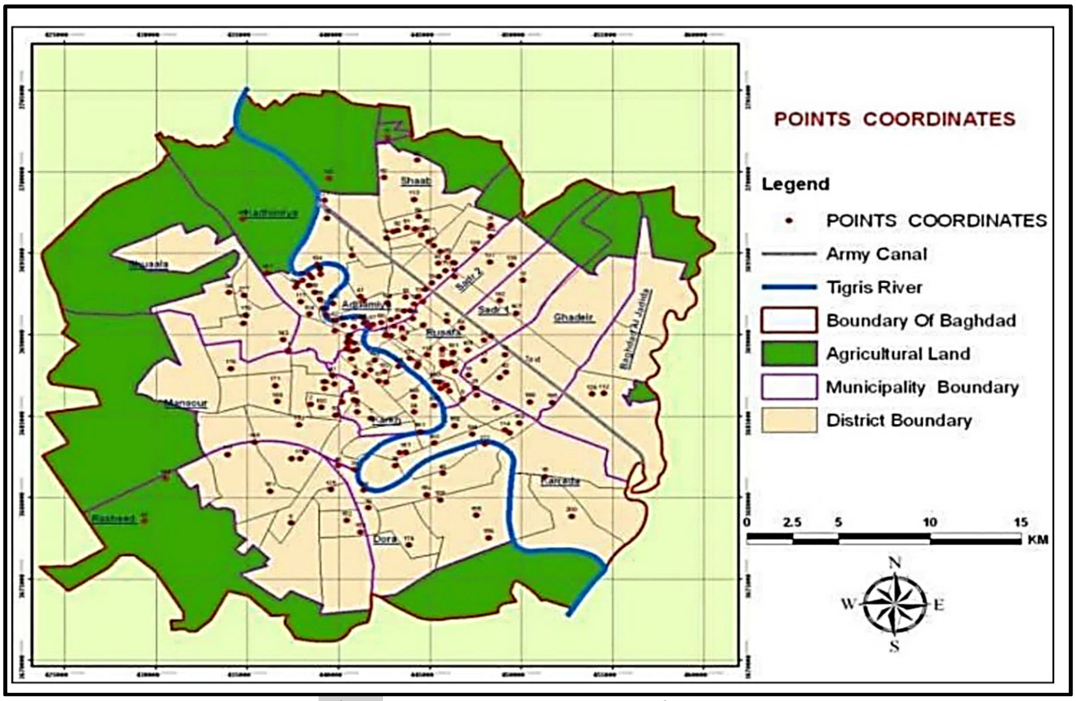


Fig.1 Site Points Location, After [17].

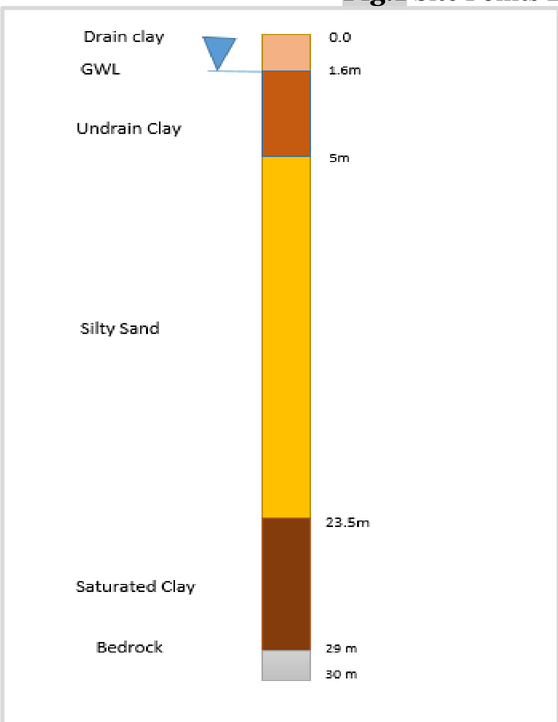


Fig. 2 The Normalized Soil Column Used in this Study.

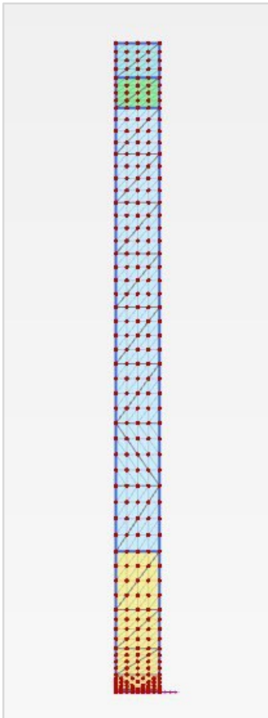


Fig. 3 The Mesh of Soil Profile that Generated by PLAXIS 2D.

Table 1 First-Layer Normalized Parameters from the Sites.

Parameter	Symbol	Value	Unit
Dry unit weight	γ_{dry}	14	kN/m^3
Saturated unit weight	γ_{sat}	21	kN/m^3
Unsaturated unit weight	γ_{unsat}	19	kN/m^3
Water content	ω	35	%
Void ratio	eo	0.5	
Cohesion	$c^{ref`}$	30	kN/m^2
Poisson's Ratio	ν_{ur}`	0.2	-
Over-Consolidation	OCR	2	-
Earth pressure Coefficient	k_o	0.87	-

Table 2 Second Layer Normalized Parameters of Silty Sand from the Sites.

Parameter	Symbol	Value	Unit
Dry unit weight	γ_{dry}	16	kN/m³
Saturated unit weight	γ_{sat}	22	kN/m³
Unsaturated unit weight	γ_{unsat}	19	kN/m³
Void Ratio	e_o	0.4	
Water Content	ω	20	%
Relative Density	D_R	57.1	%

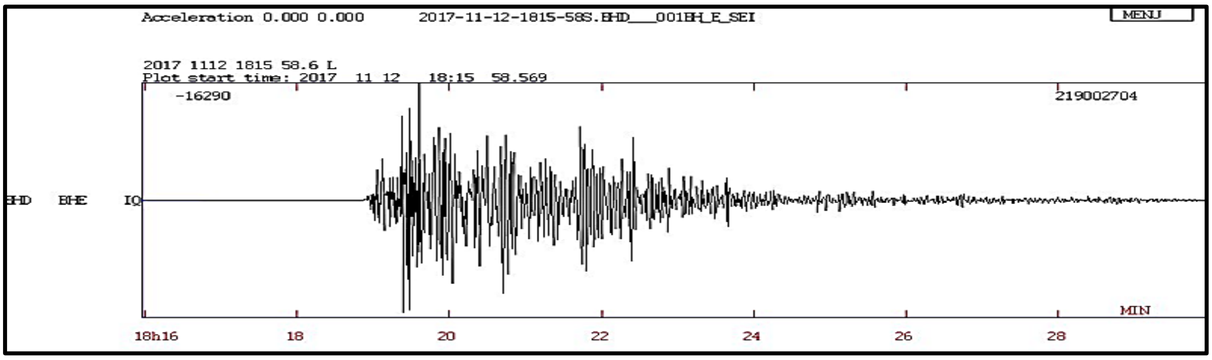
Table 3 Third Clay Layer Normalized Parameters from the Sites.

Parameter	Symbol	Value	Unit
Dry unit weight	γ_{dry}	16	kN/m³
Saturated unit weight	γ_{sat}	22.4	kN/m³
Unsaturated unit weight	γ_{unsat}	21.92	kN/m³
Water Content	ω	37	%
Void Ratio	eo	0.4	-
Cohesion	$c^{ref`}$	35	kN/m²
Poisson's Ratio	ν_{ur}`	0.2	-
Over-Consolidation	OCR	2	-
Earth Pressure Coefficient	k_o	0.87	-

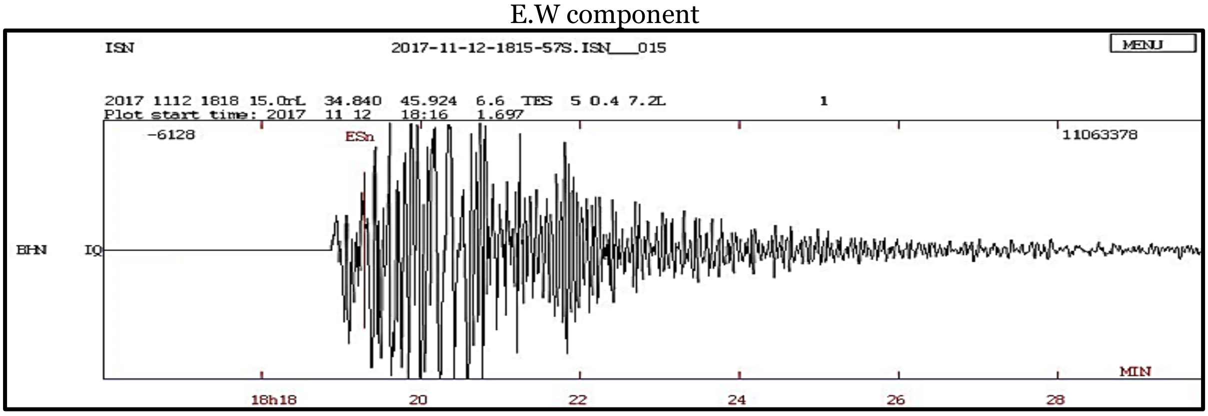
The 2017 Halabja earthquake was chosen for the current study. Halabja is a city located in the Kurdistan Region in Iraq. It is situated near the Iranian border in the country's northeastern part. Halabja lies around 240 kilometers (150 miles) northeast of Baghdad, the capital, and 14 kilometers (9 miles) east of the bigger city of Sulaymaniyah. The November 12, 2017, earthquake along the Iraq-Iran border at Halabja was a significant seismic event. The earthquakes affected a wide region, encompassing parts of Iraq, Iran, and neighboring countries. The earthquake caused significant damage to the infrastructure and fatalities. In addition to around 500 deaths, thousands of people were injured in both Iraq and Iran. Numerous buildings, including infrastructure and residential homes, suffered severe damage or were completely destroyed in the affected areas. Table 4 provides significant information about this earthquake. Fig. 4 depicts the Halabja earthquake's component (E.W, N.S., and Z component) based on a seismograph, and Fig. 5 depicts the component (E.W, N.S., and Z component) of the earthquake's temporal acceleration history [19].

Table 4 The information on the Halabja Earthquake.

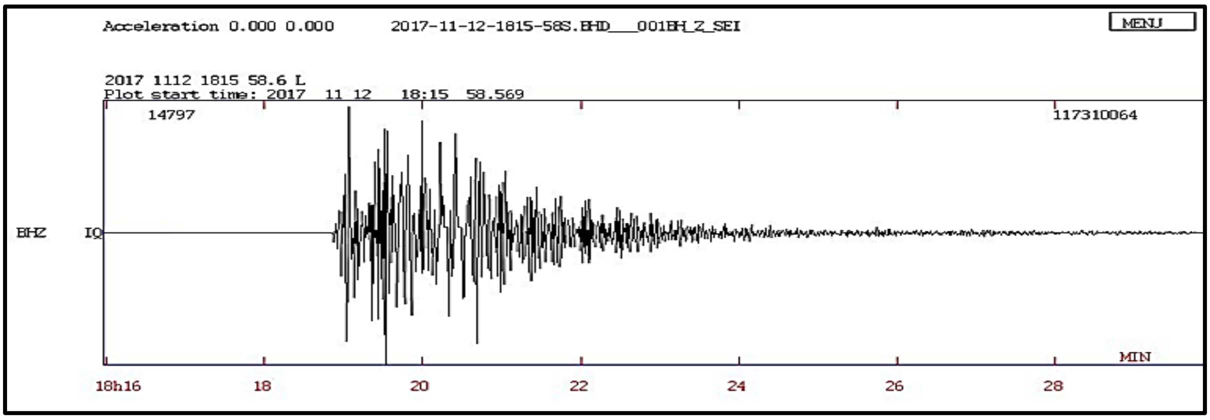
Date	Time	Lat	Lon	Depth	Earthquake intensity Ml	region
12/11/2017	18:18:15	34.840	45.924	18	7.3	Near the Iraqi-Iran border



E.W component

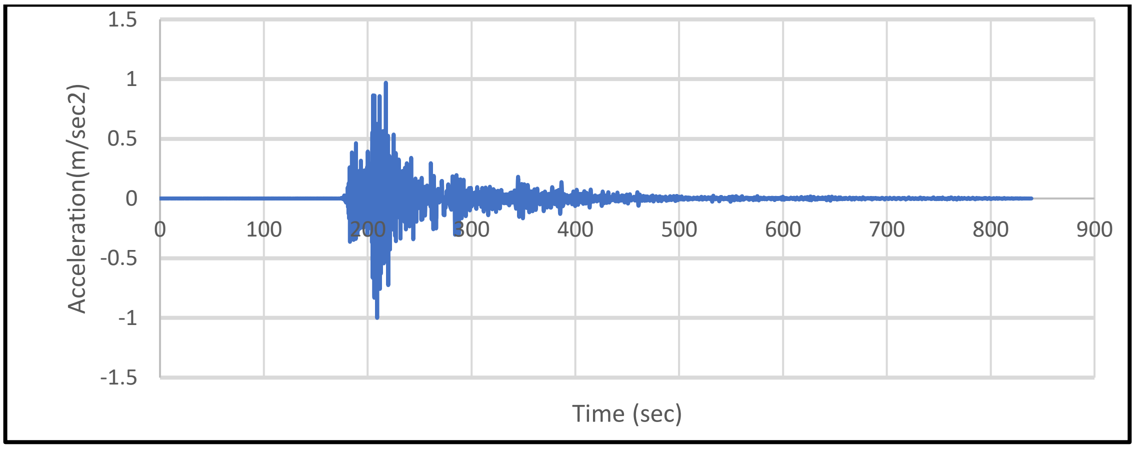


N.S component

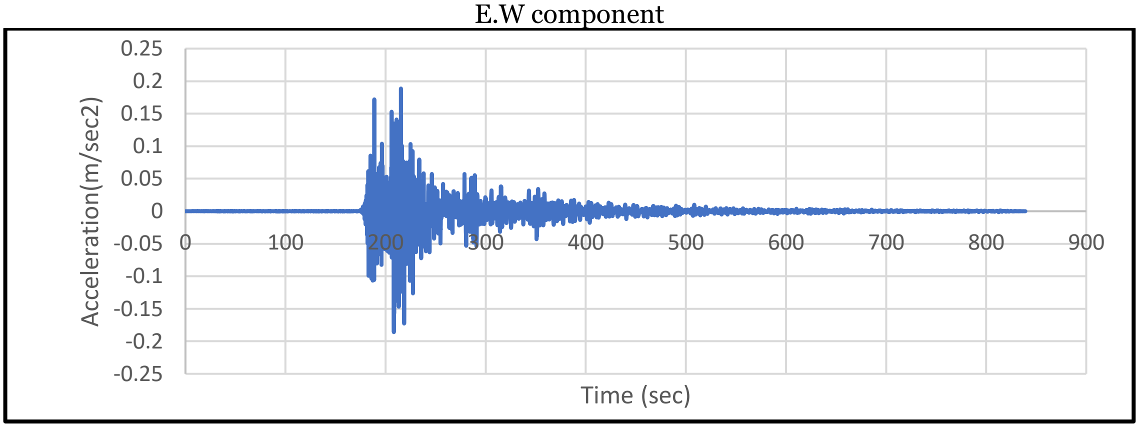


Z component

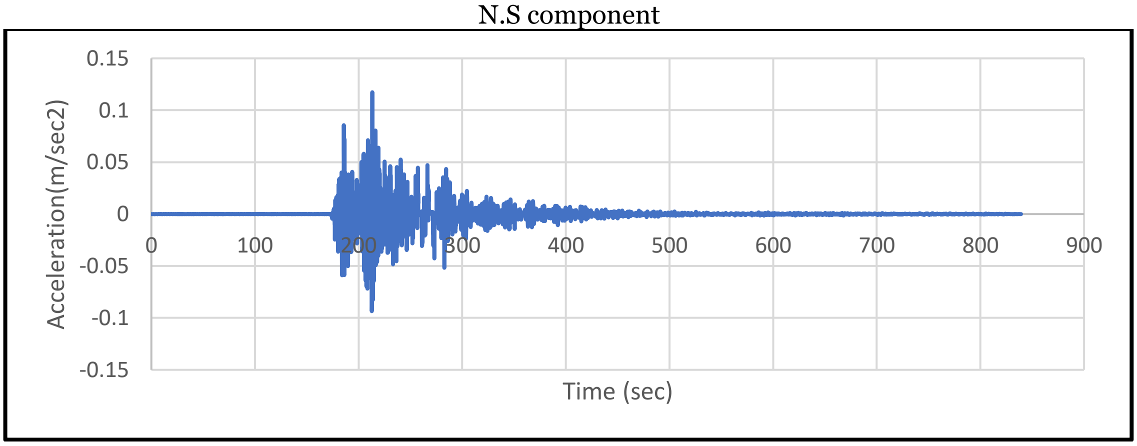
Fig.4 The component (E.W, N.S and Z component) of the Halabja earthquake by Seismograph [20].



E.W component



N.S component



Z component

Fig.5 The Component (E.W, N.S and Z Component) of Time Acceleration History of the Halabja Earthquake [20].

4.INFLUENCE OF SOIL PROPERTIES AND CONSTITUTIVE FRAMEWORKS ON LIQUEFACTION SUSCEPTIBILITY

4.1.The Impact of Relative Density (D_R)

One important factor affecting the soil's susceptibility to liquefaction is relative density (D_R). The current study considered four relative densities of silty sand: 30%, 50%, 75%, and 85%. Fig. 6 shows the relationship between the excess pore water pressure ratio (r_u) and relative density (D_R). As relative density decreases, the pore water pressure ratio (r_u) increases, assuming all other factors remain constant. The soil's ability to resist pore pressure generation was significantly influenced by its relative density. Low (D_R) soils (loose) were much more prone to higher (r_u), leading to an increase in liquefaction potential, while high (D_R) soils (dense) maintained low (r_u) and were more resistant to liquefaction [22]. It appears that if the relative density is lower than 50%, Baghdad City's silty sand soil will liquefy. Fig. 7 shows the relationship between excess pore water pressure ratio (r_u) and total displacement (U). Generally, as the excess pore water pressure ratio (r_u) increases due to loading, the total displacement (U) also increases. This is because higher (r_u) indicated a reduction in effective stress, leading to increased deformation of the soil structure. Initially, the total displacement increases as the relative density decreases (see Fig. 8). Deviatoric strain and relative density are correlated in Fig. 9. When D_R increased from 30% to 85%, the overall deviatoric strain was reduced. There is an inverse correlation between deviatoric strain and relative density (D_R) in soils. As relative density decreased (loose soils), deviatoric strain increased, and as relative density increased (dense soils), deviatoric strain decreased. This correlation is primarily due to how loose and dense soils behave under shear loading, with loose soils being more prone to deformation and dense soils being more resistant.

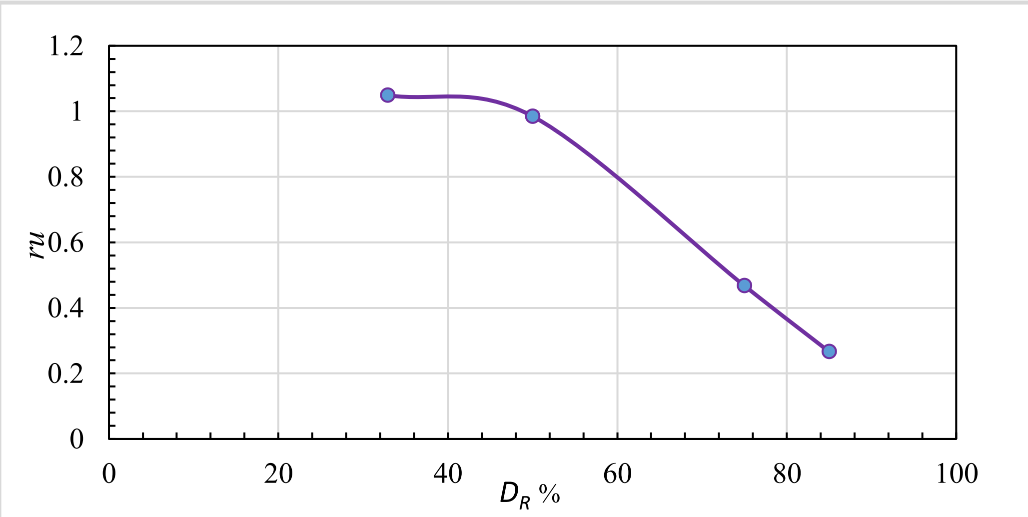


Fig.6 The Effect of Relative Density (D_R) on Excess Pore Water Pressure Ratio (r_u).

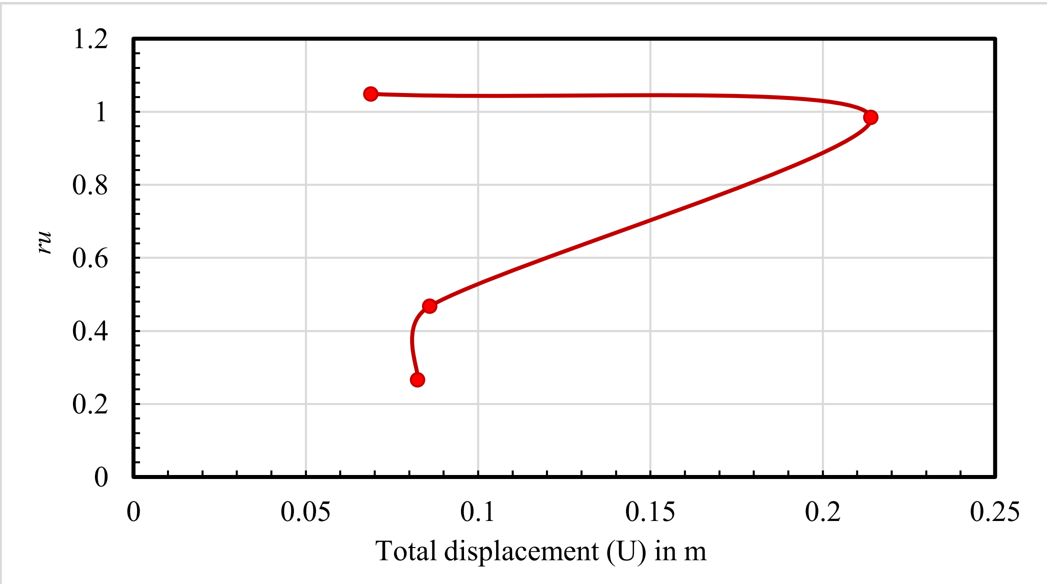


Fig. 7 The Relationship between Excess Pore Water Pressure Ratio (r_u) and Total Displacement (U).

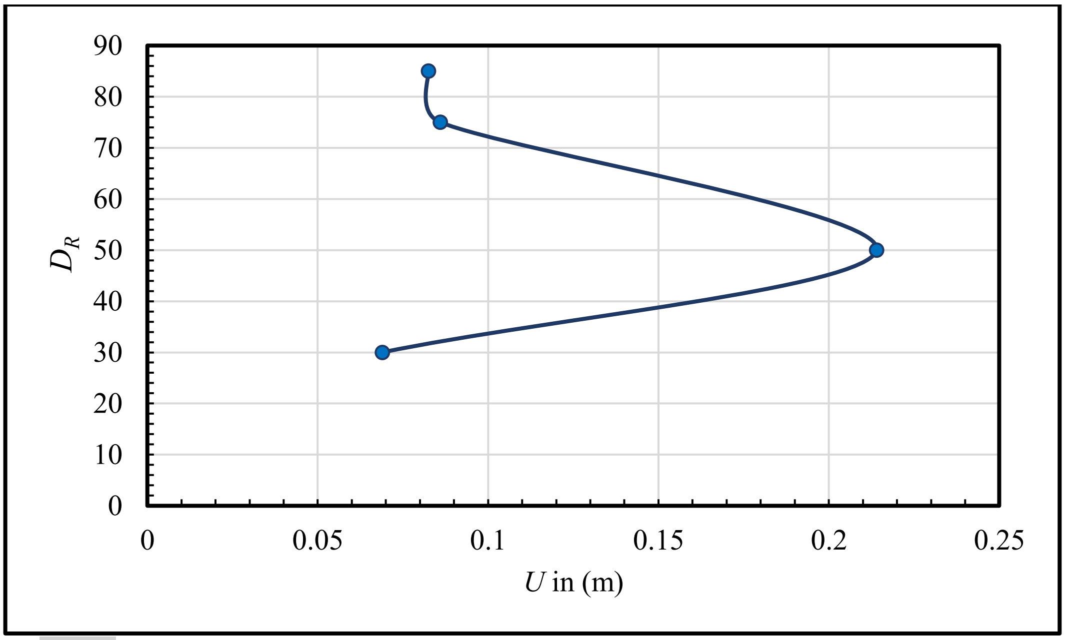


Fig. 8 The Relationship between Relative Density (D_R) and Total Displacement (*U*).

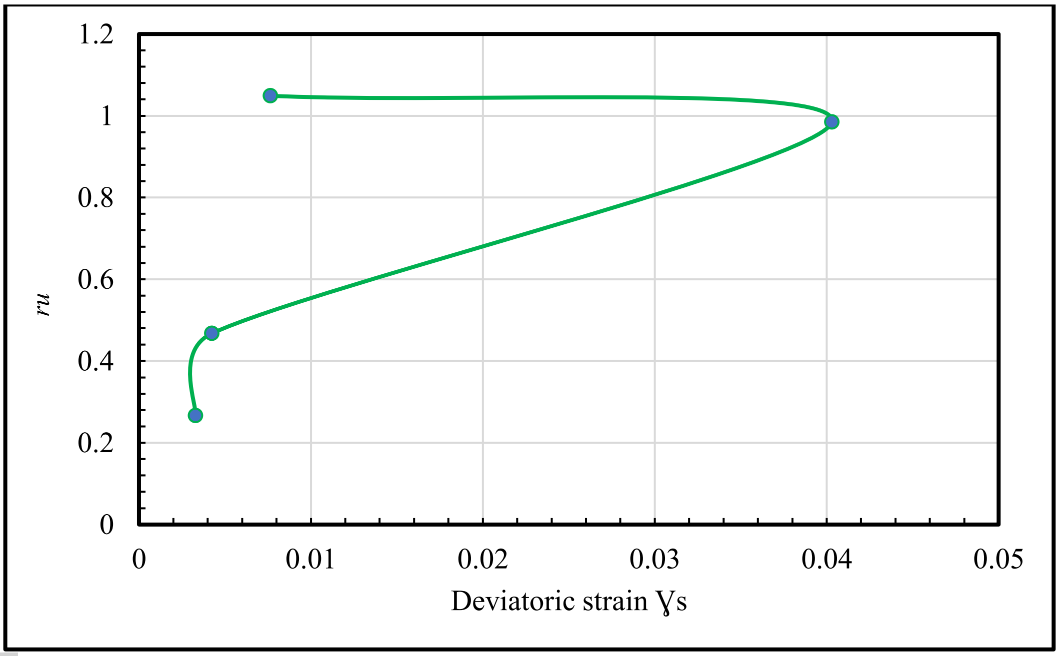


Fig. 9 The Relationship between Excess Pore Water Pressure Ratio (*ru*) with Deviatoric Strain (Ɣs).

4.1.1.Variation of Peak Spectral Acceleration with D_R

Peak Spectral Acceleration (PSA) was used in site response analyses to understand how different soil layers become stronger or weaker in response to seismic waves. These analyses helped to anticipate ground motion characteristics at different depths, as shown in Fig.10, where relative density was used as (30, 50, 75, and 85) %, respectively, to assess the potential of liquefaction.

4.1.2.Scrutinize of Baghdad Silty Sand Layer under Liquefaction

In order to determine whether Baghdad's soil is liquefiable in response to the 2017 Halabja earthquake or not, the current study will compute the excess pore water pressure ratio using the PLAXIS 2D. Fig.11 displays the excess pore water pressure ratio findings from the chosen earthquake. This implies that if the same earthquake occurs, the soil in Baghdad will liquefy. A r_u value of 0.97 is extremely close to 1, indicating that the soil is almost liquefied, and an effective stress of almost zero is approaching. This indicates that the soil has almost lost its shear strength and is susceptible to deformation, as shown in Fig.12. The results indicate that full liquefaction is triggered in the middle of the liquefiable layer. Consequently, the strain reaches the highest value since the confining earth pressure is minimal.

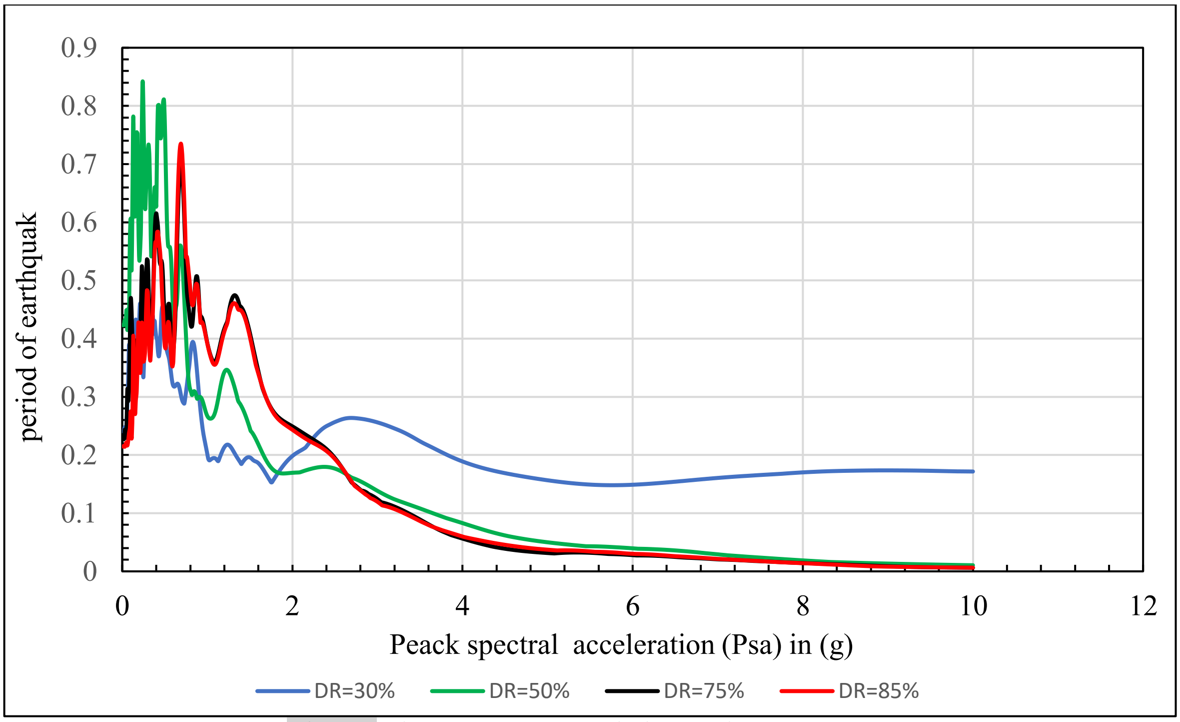


Fig. 10 The PSA (g) Depended on Relative Density.

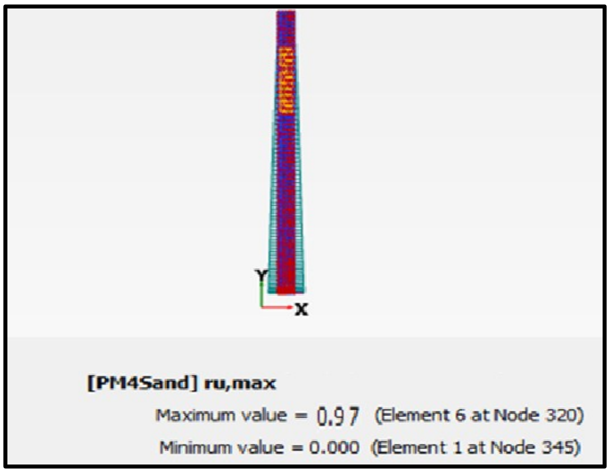


Fig.11 Excess pore water pressure ratio by PLAXIS 2D for the Halabja earthquake at Baghdad's city.

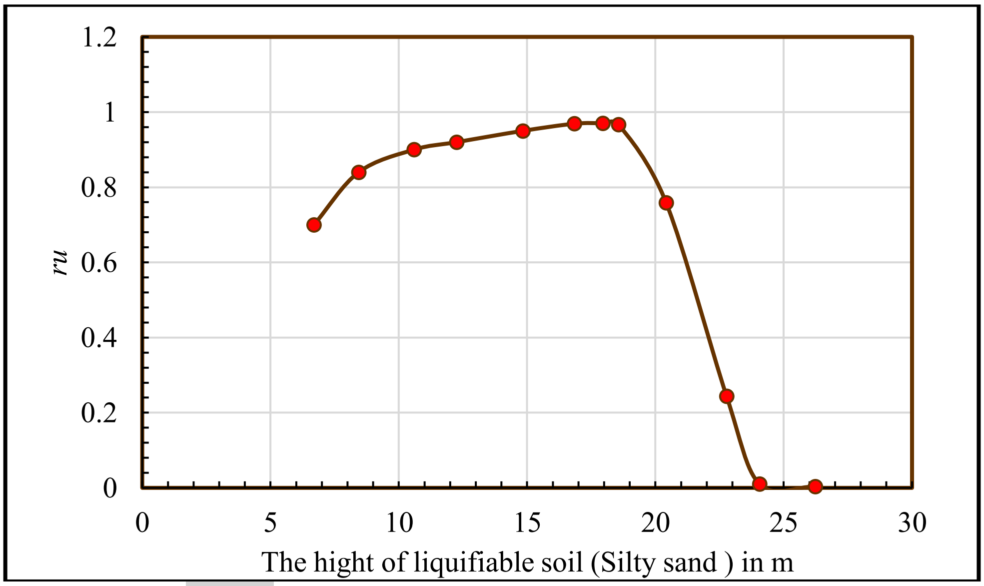


Fig. 12 The r_u at different heights of Liquefiable soil

4.2.The Impact of Initial Shear Modulus (G_o)

In this study, the values of (G_o) were taken as (35, 65, 85, 95, and 125) MPa to inspect liquefaction, displacement, and deviatoric strain, as presented earlier in Table 5. The accumulation of pore water pressure during liquefaction decreases the effective stress in the soil, which in turn lowers the soil's shear strength and stiffness. In spite of a high starting shear modulus (G_o), the strain increases sharply after liquefaction triggering.

4.3.Contraction Rate Parameter h_{po}

This parameter, which is particularly significant when considering liquefaction analysis, characterizes the rate of soil contraction under cyclic loading in constitutive models [22]. Table 6 shows the impact of this parameter on the output result from PLAXIS 2D.

4.4.Bounding Surface Parameter, n^b

The bounding surface in the stress-strain space affects shape and size, which soil behavior controls during loading and unloading cycles. Table 7 shows the impact of the bounding surface parameter on excess pore water pressure ratio (r_u), total displacement (U), and deviatoric strain (γ_s), and Fig.13 shows how excess pore water pressure ratio changes due to bounding surface parameter.

4.5.Critical State Line Parameter, R

The critical state line in this section was taken from 1.5 to 5 to see its impact on liquefaction severity, displacement, and deviatoric strain, as presented in Table 8.

4.6 Effect of Earthquake Intensity and Time Period

The properties of recent and quite intense earthquakes that occurred in Iraq, such as Ali al-Gharbi, Khanaqin, and Halabja, have been examined in this part of the study using PLAXIS 2D software. Table 9 compares earthquake intensity to excess pore water pressure ratio (r_u). Table 10 illustrates the earthquake period's effect on the liquefaction phenomenon with all other constant parameters. Fig.15 shows that the excess pore water pressure ratio increases nonlinearly when the earthquake intensity increases. Therefore, the likelihood of liquefaction may occur when the earthquake strength reaches six on the Richter scale. Fig.16 shows that when the duration of an earthquake rises, the pore water pressure increases simultaneously. From this figure, an earthquake lasting over 33 seconds could cause severe damage due to excess pore water generation.

Table 5 Values of pore water pressure (ru), total displacement (U), and deviatoric (γs) strain related to shear modulus parameter.

G_o in MPa	r_u	Total displacement (U) in m	Deviatoric strain (γ_s)
35	1.049	0.0689	7.64*10-3
65	0.9848	0.214	0.04033
85	0.4676	0.08598	4.244*10-3
95	0.2665	0.08248	3.286*10-3
125	0.199	0.0745	2.456*10-3

Table 6 Set of parameters to assess contraction rate parameter (h_{po} from 0.1 to 8).

h_{po}	ru	Maximum displacement U (m)	Total deviatoric strain (γs)
0.1	0.9850	0.1467	0.0245
0.2	0.9849	0.2505	0.03462
0.4	0.9847	0.2134	0.01870
0.6	0.9819	0.1139	9.641*10-3
0.8	0.9721	0.0855	8.56*10-3
1	0.9775	0.08792	7.607*10-3
2	0.9848	0.09121	6.720*10-3
3	0.957	0.1001	6.138*10-3
4	0.8012	0.1034	5.481*10-3
5	0.6044	0.09916	5.603*10-3
6	0.4915	0.1008	5.609*10-3
8	1.1060	0. 2212	0.05813

Table 7 Set of parameters to assess bounding surface parameter n^b.

n^b	r_u	Total displacement U(m)	Deviatoric strain (γ_s)
0.2	1.013	0.1271	0.02392
0.5	0.9847	0.2134	0.01870
0.6	0.9845	0.1437	0.01825
1	0.9836	0.06273	0.010191
3	0.988	0.0887	0.04269
5	1.031	0.1497	0.02357

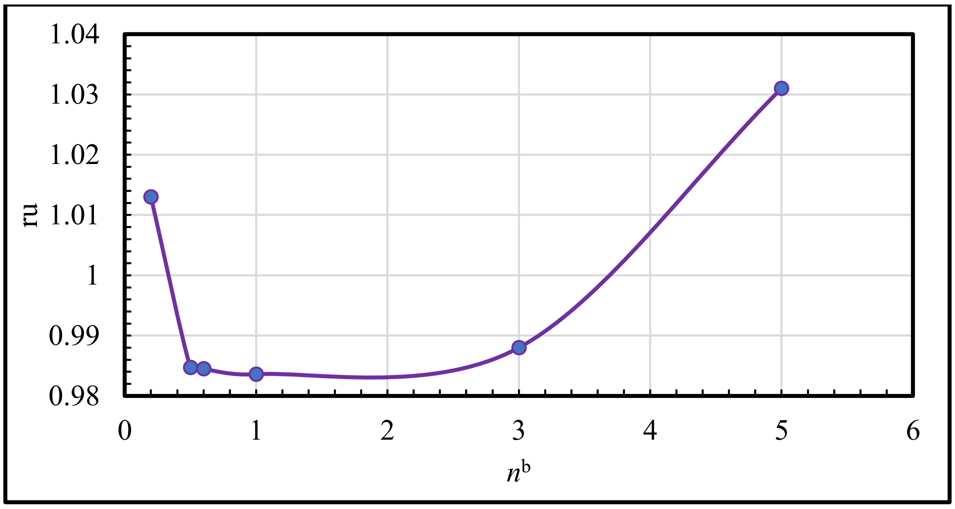


Fig. 13 The Effect of Bounding Surface Parameter (n^b) on Excess Pore Water Pressure Ratio *(ru)*.

Table 8 Set of Parameters to Assess Critical State Line Parameter.

R	r_u	Total displacement U(m)	Deviatoric strain (γ_s)
1.5	0.9847	0.2134	0.0187
2	0.9845	0.2148	0.03781
2.5	1.009	0.1081	0.03439
3	0.9879	0.03688	0.02137
3.5	1.025	0.0864	0.02001
5	0.3263	0.04630	0.05139

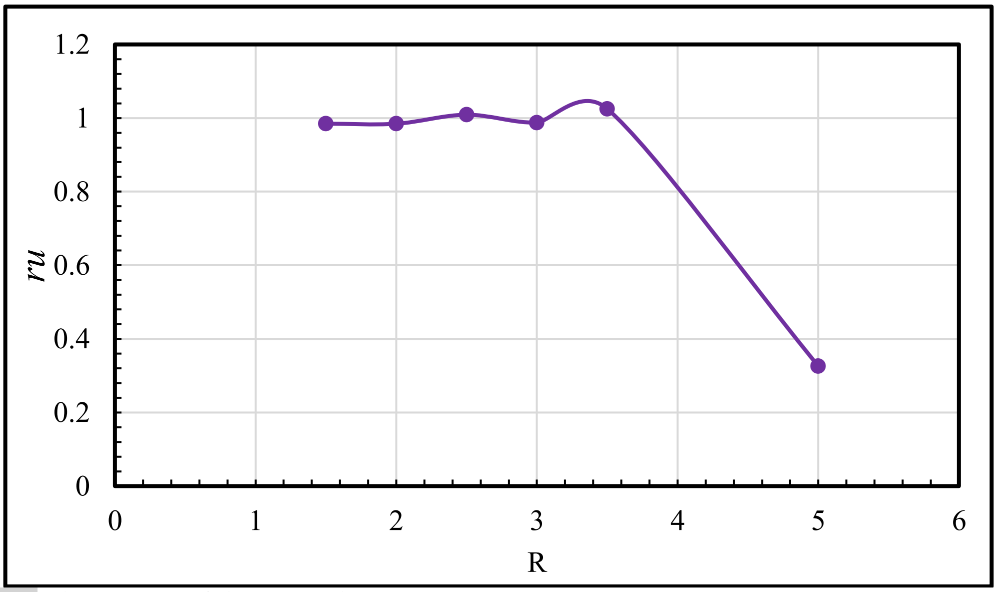


Fig. 14 The Impact of the Critical State Line Parameter on Excess Pore Water Pressure Ratio**.**

Table 9 The Values of the Excess Pore Water Ratio (ru) Depending on the Earthquake Intensity.

The Earthquake	The Earthquake Intensity (Ml)	The Excess Pore Water Ratio (r_u)
Ali al-Gharbi	4.9	0.816
Kanaqin	5.6	0.932
Halabja	7.3	1.12

Table 10 The values of excess pore water ratio (ru) depending on the earthquake period

Time in second	r_u
10	0.304
20	0.604
30	0.911
40	1.12

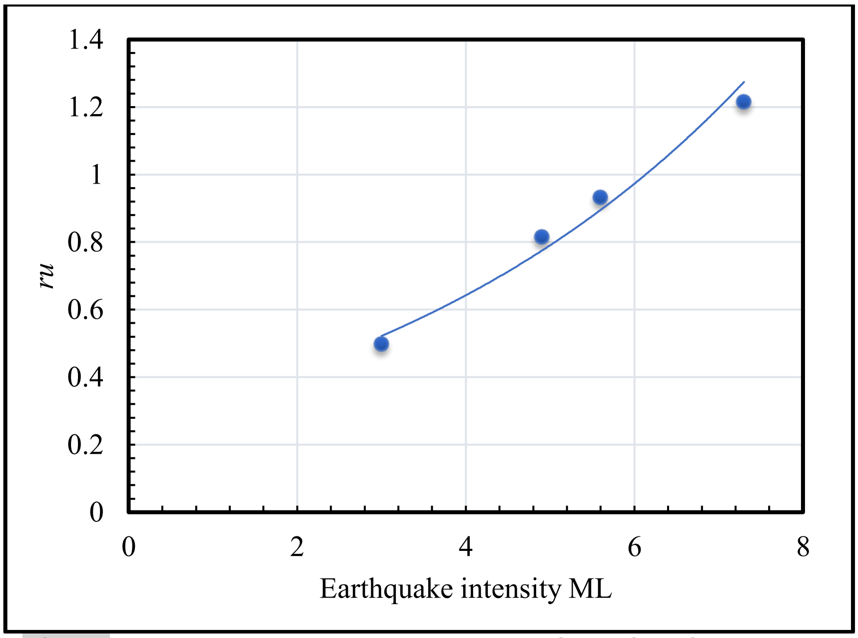


Fig. 15 Excess Pore Water Pressure Ratio with Earthquake Intensity.

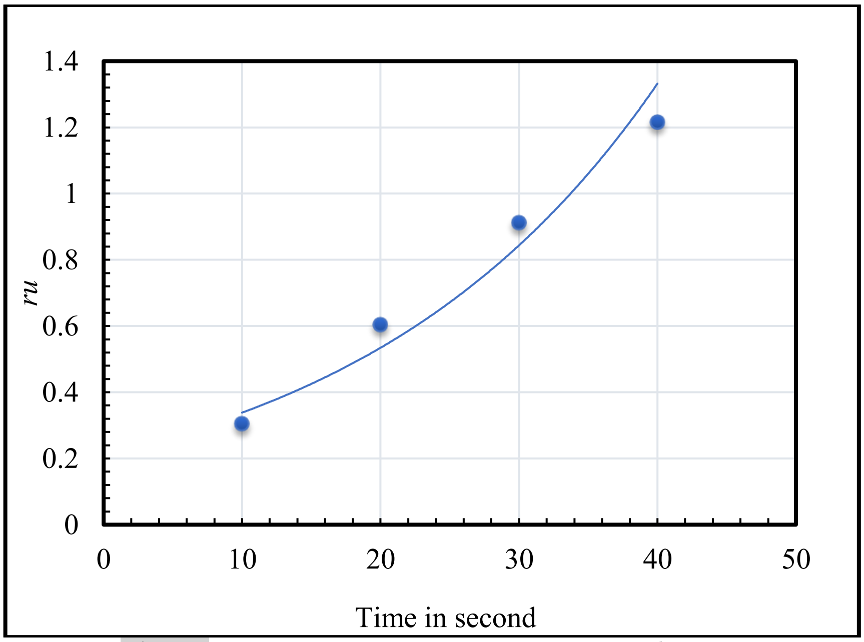


Fig. 16 Excess Pore Water Pressure Ratio with Time.

5.CONCLUSIONS

This study demonstrates how the PM4Sand model in PLAXIS may be used to examine sandy soils subjected to seismic events, with a specific emphasis on the soil of Baghdad. The results show that the relative density (D_R) and the initial shear modulus (G_o) affect soil behavior during earthquakes. When D_R is high, the soil expands, and excess pore water pressure is minimized. Liquefaction is more likely to occur when D_R is low. When shear modulas decrease (G_o), soils are less likely to liquefy because they are less pliable, better absorb seismic energy, and resist deformation. Liquefaction is more likely to occur in soils with higher R values and contraction rates under cyclic loads (higher h_{po}) because of the quick build-up of excess pore pressure. As the earthquake's magnitude increased from 4.9 Ml to 7.3 Ml, there was a noticeable rise in the r_u values, indicating a significant link between seismic intensity and pore water pressure. Findings from the study suggest that Baghdad's soil is susceptible to liquefaction, which was evident during the 2017 Halabja earthquake. The study emphasizes the importance of reducing this vulnerability, including strengthening buildings and creating evacuation plans for high-risk regions.

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NOMENCLATURE

r_u	Excess pore water pressure ratio
$r_{u\,max}$	Maximum excess pore water pressure ratio
D_R	Relative density
G_o	Initial shear modulus
h_{po}	Contraction rate parameter
n^b	Bounding surface parameter
R	Critical state line parameter
U	Total l displacement
$C^{ref`}$	Cohesion
K_o	Earth pressure coefficient
Greek symbols	
γ_{dry}	Dry unit weight
γ_{sat}	Saturated unit weight
γ_{unsat}	Unsaturated unit weight
ω	Water content
e_0	Initial void ratio
γ_s	Deviatoric strain
ν_{ur}	Poisson's ratio for unloading-reloading

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