Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (45) No. (2) October. 2023

Seismic Response of Ground Beams in Framed Structures

M.O.A. Ismail [1], H.A.M. Elarabaty [2], Akram Mostafa [3]

[1] (Postgraduate Researcher / Ain shams university, Egypt).
[2] (Professor of Structural Analysis and Mechanics / Ain shams university, Egypt)
[3] (Doctor of Structural Analysis and Mechanics / Ain shams university, Egypt)
Corresponding Author E-mail: cengmohammedosama@gmail.com

الملخص العربي:

157الميد هي عناصر إنشائية تربط بين عمودين أو أكثر لجعل المنشأ بأكمله يعمل كجزء واحد مما يجعله أكثر صلابة وثباتا. وتنص الاكواد العالمية علي اهمية ربط الاساسات السطحية بميد في اتجاهين متعامدين وتصمم هذه الميد لتحمل حمل متصل ثابت لا يقل عن q1 (القيمة الموصي بها هي 10 كيلو نيوتن / متر) طبقا للكود الاوروبي او تصمم لتحمل حمل محوري سواء كان شد او ضغط لا يقل عن 10% من قيمة SDS مضروبة في أكبر حمل رأسي على أي من العمودين قبل حدوث الزلزال طبقا للكود الامريكي او تصمم لتحمل حمل محوري سواء كان شد او ضغط لا يقل عن 10% من قيمة SDS مضروبة في أكبر حمل رأسي على أي من العمودين قبل حدوث الزلزال او عن 25% من قيمة اصغر حمل راسي علي اي من العمودين قبل حدوث الزلزال ايهما اقل وفقا للكود الدولي للمباني و يعتمد SDS على نوع التربة وقيمة العجلة الأرضية. يمكن الاستنتاج من قيم التي سبق ذكرها أنه تم تجاهل بعض العوامل المهمة (نوع المنشأ وعدد الادوار وطول وقطاع الميد). لأخذ تأثير هذه العوامل يجب قياس القوى المتولدة على الميد بدقة ودراسة القوى المتبادلة بين التربة والمنشأ. وهناك طريقتان رئيستان لدراسة القوى المتبادلة بين التربة والمنشأ. الطريقة الاولى تسمى طريقة البنية التحتية وفى هذه الطريقة نعامل التربة على انها زنبرك متعدد الاتجاهات والطريقة الثانية تسمى الطريقة المباشرة وفي هذه الطريقة نقوم ببناء نموذج عددي كامل للمنشأ والتربة المحيطة به.

158 يمكن تلخيص الأهداف الأساسية لهذه الدراسة البحثية على النحو التالي؛ دراسة آثار تفاعل تربة التأسيس مع المنشأ على الأداء الزلزالي للمنشآت الهيكلية، وكذلك دراسة تأثير ترشيح التربة وانتشار الموجات خلال طبقات التربة على المنشأ وايضا دراسة تأثير أحمال الزلازل على المنشأ الهيكلي في حالة وجود الميد وحالة عدم وجود الميد، وتعيين القوى المتولدة في الميد الناتجة عن أحمال الزلازل ومقارنتها بالقيم الموجودة في الاكواد العالمية.

الكلمات الدالة: تداخل تربة التأسيس، ترشيح التربة وانتشار الموجات، دراسة تأثير أحمال الزلازل على المنشأ الهيكلي ، سلوك الميد تحت الأحمال الزلزالي .

ABSTRACT

Design standards require that the tie beams, which join the individual footings of the structure in two directions, usually at right angles, have a tension or compression design strength that works. This strength should be equal a minimum downward load of q1 (10 kN/m recommended value) according to Eurocode 2 (ECS I-1992), should be equal 10% of SDS multiped by the maximum compression force in the columns, which the tie beam is connecting, in the factored ultimate case according to American Society of Civil Engineers (ASCE 7-16) or should be equal the lesser of 10% of SDS multiped by the maximum compression force in the columns, which the tie beam is connecting, or 25% multiped by

the minimum compression force in the columns, which the tie beam is connecting, in the factored ultimate case according to the International Building Code (IBC 2009), SDS is effected by the type of soil and seismic ground motion. The values of the aforementioned codes show that several crucial factors such as the building's structural system, number of floors, ground beam span, location, and cross-section were overlooked. In contemporary soil-structure interaction models, the substructure approach and the direct analysis methodology are the two main methodologies employed. The fundamental objectives of this research study can be summarized as follows: creating a numerical model that can depict how time historical motion at the rock layer affects the seismic response of framed constructions, examining how waves travel across soil layers and how soil filtering affects shape, frequency, and behaviour Examine how the seismic loads affected the framed structure both before and after the ground beams were added. Find out how much strain the earthquake caused on the ground beams, then compare that information to the relevant numbers from the international codes.

KEYWORDS: soil structural interaction, seismic wave propagation, Seismic Response of Ground Beams.

1 Introduction

Ground beams are structural elements that connect two or more columns to make the whole structure stiffer and more stable and to control and minimize differential settlement between adjacent footings. Moreover, it is also used to support ground walls, resist seismic loads and reduce the effective buckling length of columns.

The tie beams that connect the separate footings of the structure in two directions—typically at right angles—must have a tension or compression design strength that complies with design regulations. This strength should be equal a minimum downward load of q1 (10 kN/m recommended value) according to Eurocode 2 (ECS I-1992) [1], should be equal 10% of SDS multiped by the maximum compression force in the columns, which the tie beam is connecting, in the factored ultimate case according to American Society of Civil Engineers (ASCE 7-16) [2] or should be equal the lesser of 10% of SDS multiped by the maximum compression force in the columns, which the tie beam is connecting, or 25% multiped by the minimum compression force in the columns, which the tie beam is connecting, in the factored ultimate case according to the International Building Code (IBC 2009) [3], SDS is effected by the type of soil and seismic ground motion. The values of the aforementioned codes show that several crucial factors such as the building's structural system, number of floors, ground beam span, location, and cross-section were overlooked.

The seismic behavior of a structure is not only influenced by the superstructure’s response, but also by how the soil under its foundation reacts, as many academic publications have shown in recent years. According to Federal Emergency Management Agency (FEMA 2020) [4], there are two main approaches that are now utilized in models to take into account for the interaction between soil and structure. The first approach, the substructure approach models the soil as discrete multi-directional springs, and the second approach is the direct analysis approach, which will be used in this thesis, with only one finite element approach, the building's structure, foundations, and underneath soil are all modeled.

2 Model and verification of 3D finite elements

Using the finite element program Sap2000 [5], an improved soil-structure numerical model is created to simulate seismic wave propagation and the impact of soil-structure interaction. The direct approach is used to study the effect of soil structure interaction and the validity of the finite element model is tested by comparing it with a shaking table test conducted by (Xiaofeng Zhang and Harry Far 2021) [6].

2.1 Structural Model

The model of the structure for shaking table tests is a frame structure with 15 stories (height = 45m), a total mass of 953 tonnes, and a natural frequency of 0.384 Hz. It is built on a shallow foundation on clay soil with a maximum shear modulus of 3310 tons/m^2 and a soil density of 1.47 tons/m^3.To achieve dynamic similarity, (Xiaofeng Zhang and Harry Far 2021) [6] followed the method described by (Meymand 1998) [7] for the shaking table test and the geometric scaling factor (λ) used was 1:30; therefore, the dimensions of the prototype are 1.5 m height and 0.4 m width and the natural frequency of the scaled model is 2.11 Hz. Shell, frame and solid elements in Sap 2000[5] were used to model slabs, columns and foundations. For more information about the shaking table tests, refer to (Meymand 1998) [7], (Tabatabaiefar 2014) [8], (Fatahi 2015) [9], (Tabatabaiefar 2016) [10] and (Tabatabaiefar and Mansoury 2016) [11]. The scaled frame construction has a damping ratio of around 1.1%, according to shaking table measurements. Hence, two damping coefficients α and β can be calculated as 2.297 and 0.0004 from the first and second vibration frequencies of the structure. Figure 1 shows the scaled frame structure's 3D numerical model, the model's material characteristics, and the shaking table test are shown in.

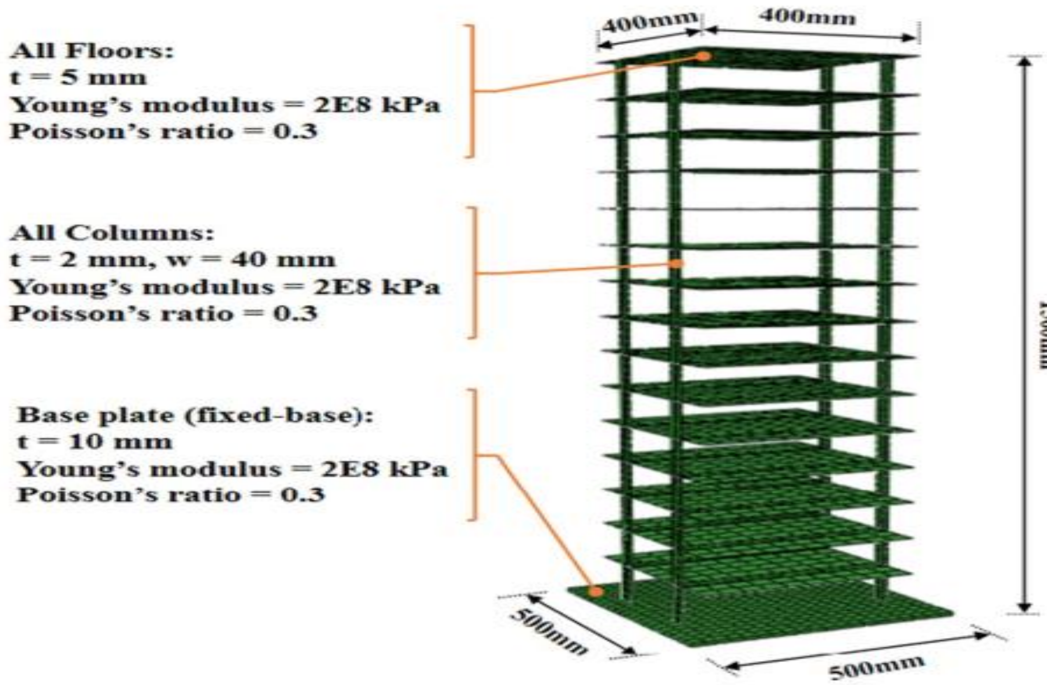

Figure 1: 3D numerical model of this scaled frame structure in ABAQUS presented in (Xiaofeng Zhang and Harry Far 2021). [6]

2.2 Soil Model

A 3D eight-node element with reduced integration is used to model the soil element and the Mohr-Coulomb model is applied. Soil-structure interaction is modelled using a one-parameter Winkler soil model. The completely nonlinear approach is a widely used technique to account for soil nonlinearity when computing wave propagation or seismic response in soil. The nonlinear backbone curves proposed by H. Bolton Seed, F. ASCE 1986) [12] and Joseph Sun., H. B. Seed 1998) [13] are utilized to derive the shear modulus reduction, cyclic shear strain, and to compute the damping ratio in order avoid the usage of nonlinear analysis.

2.3 Soil Boundary

This study uses the 3D viscous-spring boundary proposed by (Liu Jingbo and Du Yixin 2006) [14]. To calculate the mechanical coefficients of the spring, which depend on the property of the surrounding soil medium, the following formula is used. The spring and dampers are placed in parallel in one normal and two tangential directions of the boundary nodes..

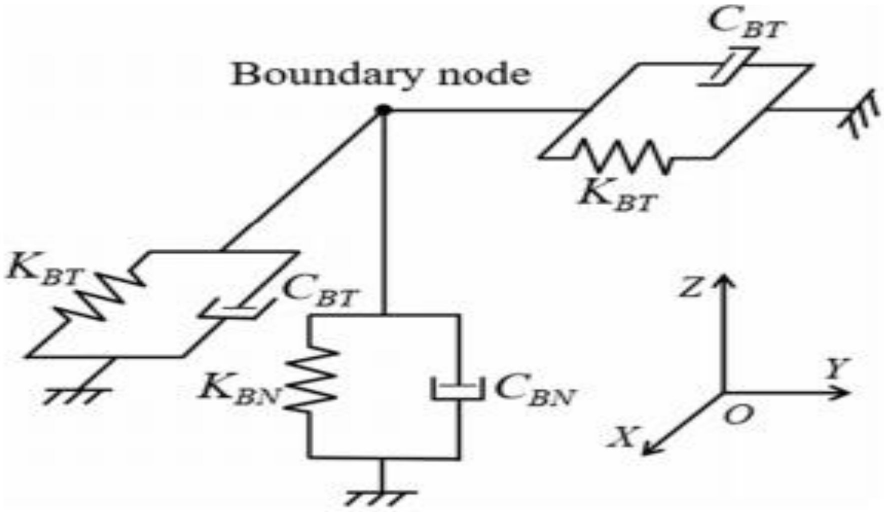

Figure 2: Viscous-spring boundary presented in (Liu Jingbo and Du Yixin 2006) [5].

K_{BT}= [α_T] [G]/[R] C_{BT}= [ρ] [C_S]

K_{BN}= [α_N] [G]/[R] C_{BN}= [ρ] [C_P]

Where α_T= (0.5-1) and α_N= (1-2) according to (Liu Jingbo and Du Yixin 2006) [14].

2.4 Finite Element Model Verification

Two earthquakes, El Centrro and Kobe (Table 1), are simulated using sap2000 software on a 15-story framed building situated on clay soil in order to examine the viability of the finite element method described in these earlier sections and compared with the shaking table test conducted by (Xiaofeng Zhang and Harry Far 2021) [6]. Figure (3) shows the difference between the analytical model and the experiment with El Centro and Kobe earthquakes (-3.77% and 1.52% respectively).

Table 1: Earthquake ground motions used in this study

Earth-quake	Country	Year	PGA (g)	Mw (R)	Dura- tion (s)	Type	Hypocentral distance (km)	Rord
El Centro	USA	1940	0.349	6.9	56.5	Far field	15.69	Bedrock record
Kobe	Japan	1995	0.833	6.8	50.0	Near field	7.4	Bedrock record

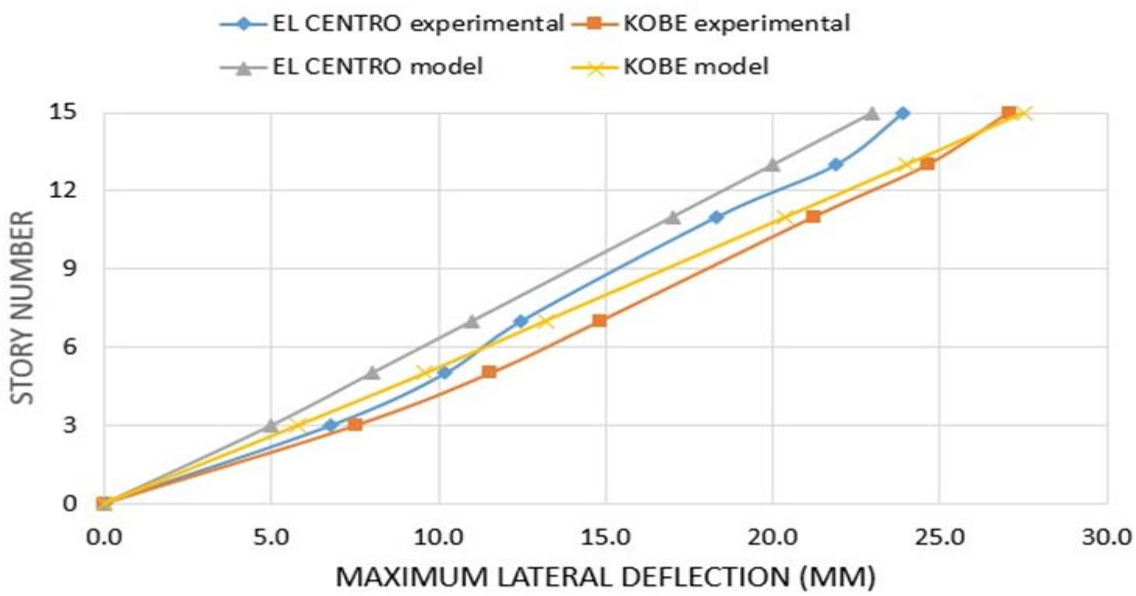

Figure 3: shows a good resemblance between the results obtained from the analytical model and the experiment

3 Parametric Study

The framed structure used in the parametric study consists of 5 spans in X and Y directions and it is designed according to Egyptian codes for design and construction of buildings (ECP 203-2018) [15]. the parametric study was done for different soil types according to (ECP 201-2012) [16] (type B, type C and type D) (table 2 shows soil properties and figures 5 and 6 show the nonlinear backbone curves introduced by (H. Bolton Seed, F. ASCE 1986) [12] and (Joseph Sun., H. B. Seed 1998) [13]) show the shear modulus reduction, cyclic shear strain and the), seismic ground acceleration (0.15g, 0.2g, 0.25g and 0.3g), the ground beams location (at foundation level and slab on grade level), the distance between building's footings and bedrock (10, 20 and 40m), the span of the ground beams (4, 6 and 8m), the inertia of ground beams (Iground beam/Ibeam = 1, 4 or 8) and the framed structure number of stories (4, 6 and 8 stories). The damping ratio is assumed to be 7%. The grade of the concrete used in the studied framed structures= 35Mpa and the yield strength of the steel used in the studied structures =350Mpa. Earthquake excitation is implemented using seismic central motion at the model bedrock level. Artificial earthquake time history by (Abdel-Motaal 1999) [17] (Figure 4), is used after scaling to simulate the target earthquake intensity or maximum acceleration.

Table 2 Soil properties used in this study

Soil type	Soil name	Bearing capacity (kPA)	Cohesion (kPA)	Friction angle (Deg)	Density (KN/m^3)	Maximum shear modulus (MPA)	Stiffness (MPA)
B	Dense sand	200	0	38	20	250	100
C	Silty sand	150	0	33	18	150	50
D	Clayey silt and sand	125	20	22	15	100	30

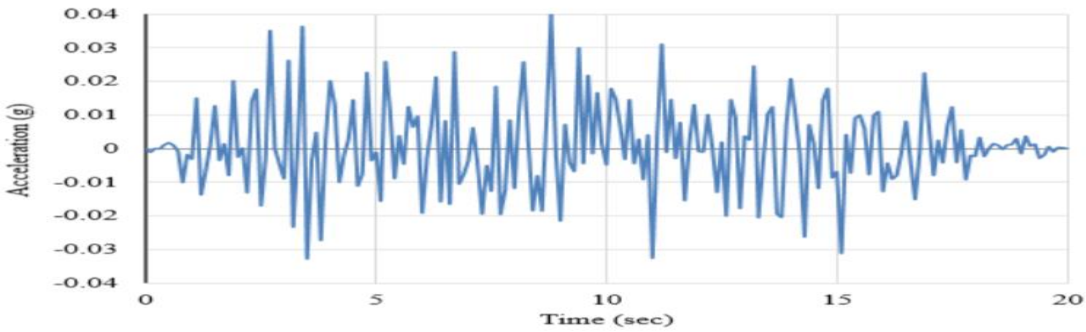

Figure 4 Time-acceleration history of the artificial earthquake

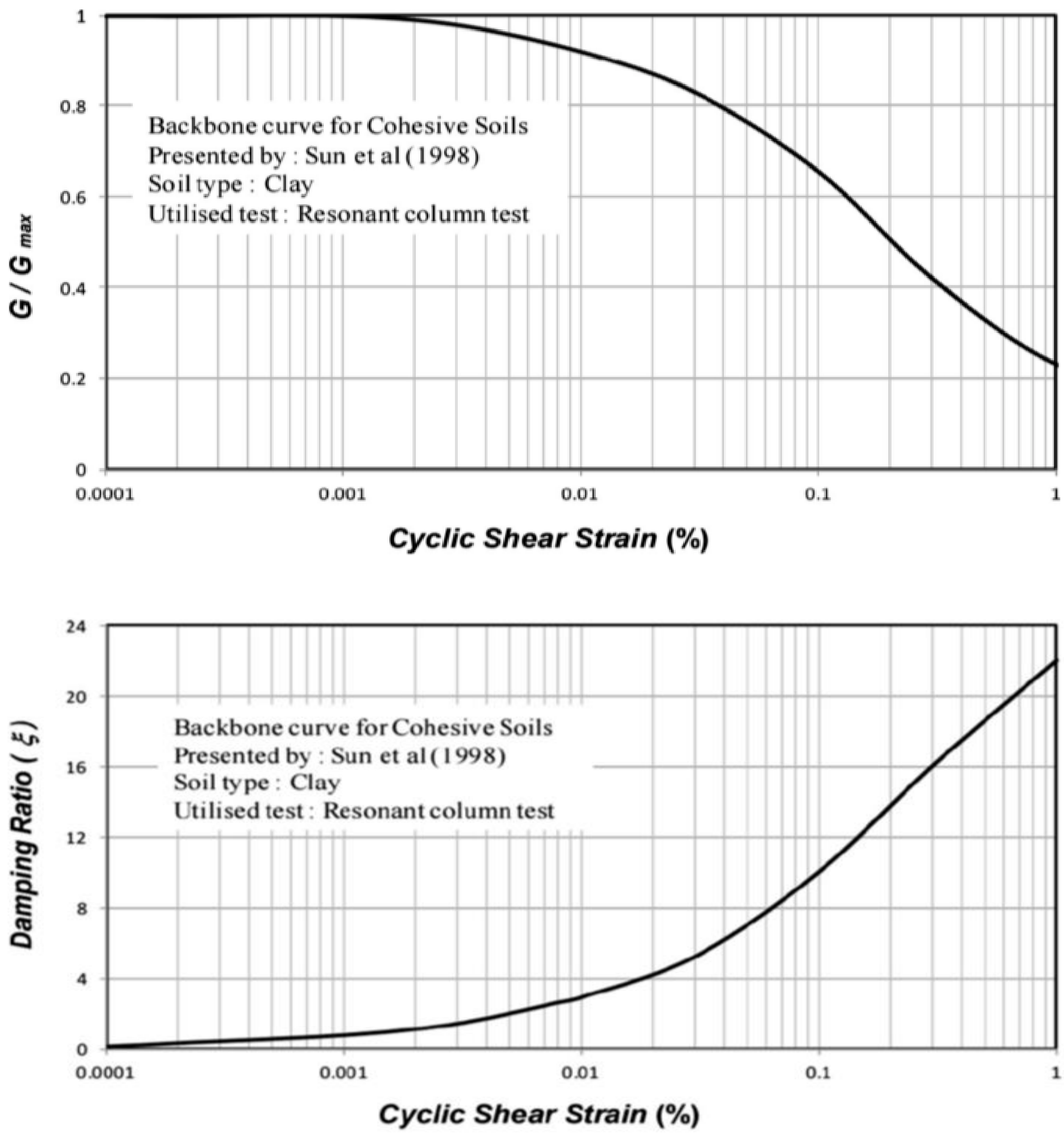

Figure 5: The first graph depicts the Relationship between G/Gmax versus γc for cohesive soils, while the second graph depicts the Relationship between ξ versus γc for cohesive soils (Presented in (Joseph Sun., H. B. Seed 1998)) [13].

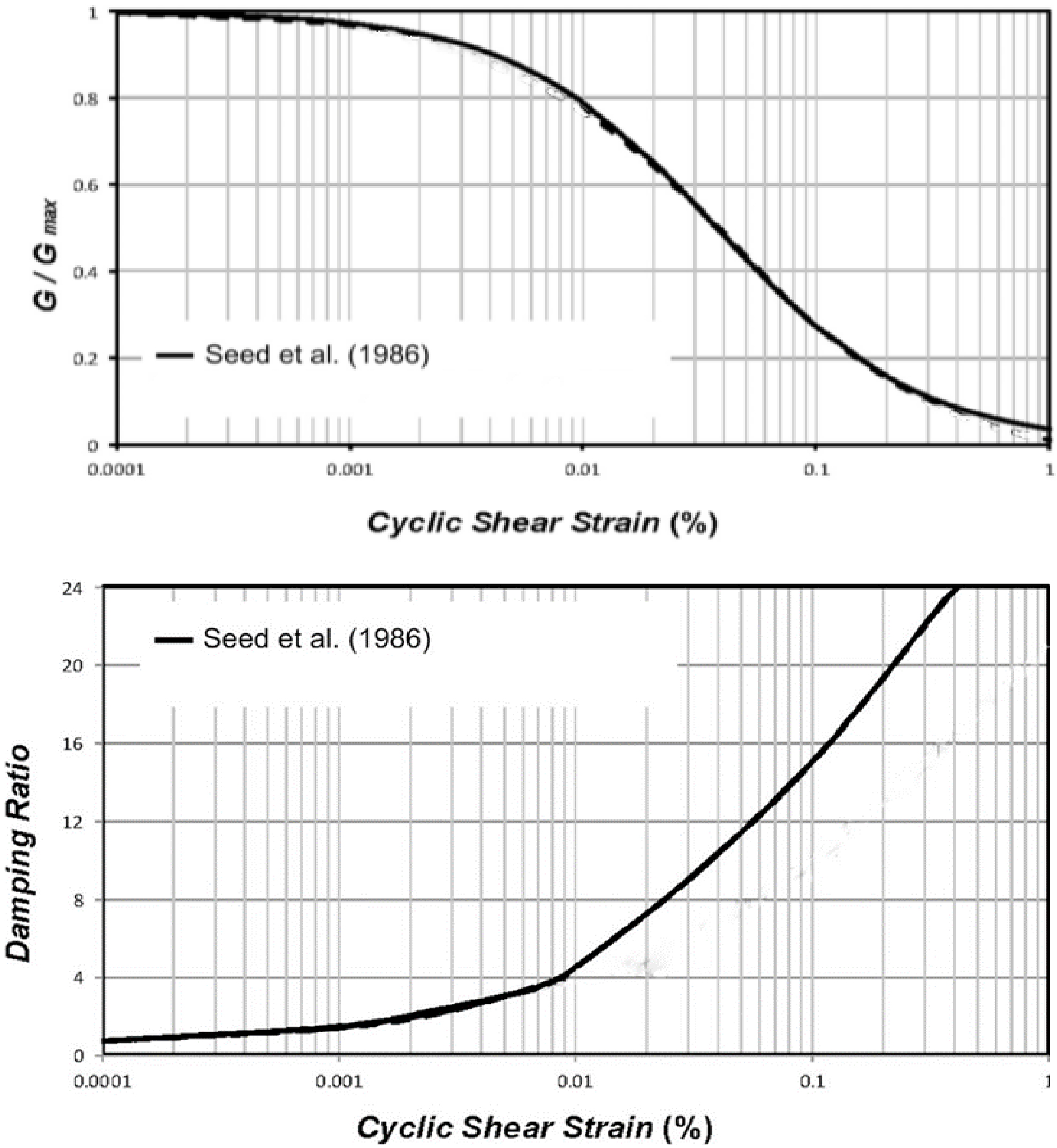

Figure 6: The first graph depicts the Relationship between G/Gmax versus γc for cohesionless soils, while the second graph depicts the Relationship between ξ versus γc for cohesionless soils (presented in (H. Bolton Seed, F. ASCE 1986) [12]).

4 Results and Discussion

In this section, the results of the parametric study are displayed and reviewed. For each framed structure, tie beams are designed, and the design process values are compared to the corresponding values from various international codes (Eurocode 2 (ECS I-1992) [1], the International Building Code (IBC 2009) [3], and the American Society of Civil Engineers (ASCE 7-16) [2].

4.1 Seismic Design for Tie Beams

The introduction shows that the codes' values do not consider some important factors, such as the location and the building's structural system, column spacing, and number of floors. These parameters are studied separately in this section without neglecting the considered parameters by the building codes (soil type and seismic ground motion). The maximum results obtained from the finite element model is compared with the corresponding values in the codes and the effect of each previously mentioned parameters is shown separately.

4.1.1 The Effect of The Soil Type

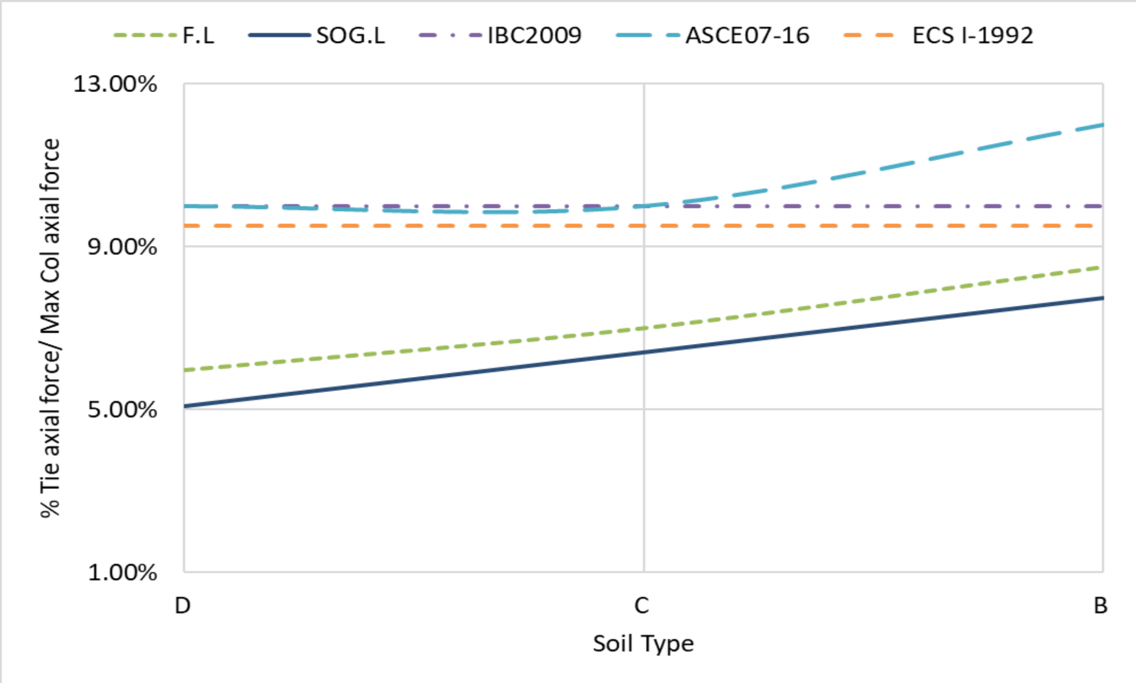

Figure 10: The relationship between the percent Tie axial force / maximum column axial force and Soil Type

Figure 10 shows that the ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force increases significantly with the soil shear modulus for all studied framed structures as the SSI effect deceases with the increase of the shear modulus; consequently, increasing the straining actions in the tie beams. Furthermore, the examined ratio is marginally greater when the tie beams are positioned in the foundation level as opposed to the slab on grade level, and the code values for the three codes that were employed are higher than the findings from the finite element model.

4.1.2 The Effect of The Seismic Ground Acceleration

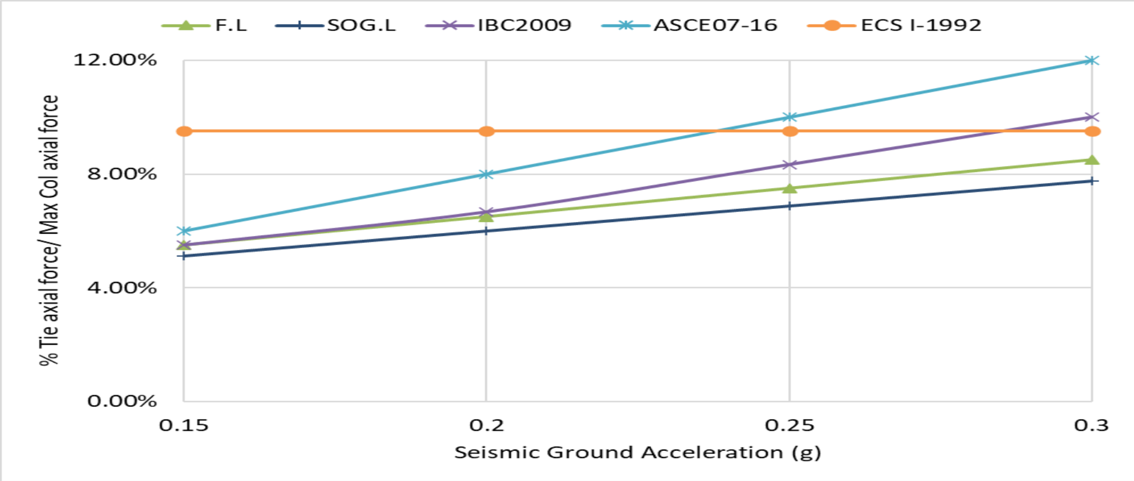

Figure 11: The relationship between the percent Tie axial force / maximum column axial force and maximum seismic ground acceleration

Figure 11 shows that the ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force increases significantly with the seismic ground acceleration for all studied framed structures as the actual motion under the studied framed structures foundation rises with the increase of seismic ground acceleration; consequently, increasing the straining actions in the tie beams. Moreover, the code values for the 3 used codes are higher than the results obtained from the finite element model, and the studied ratio is slightly higher when the tie beams are located in the foundation level than when they are located in the slab on grade level.

4.1.3 The Effect of The Spacing Between Columns

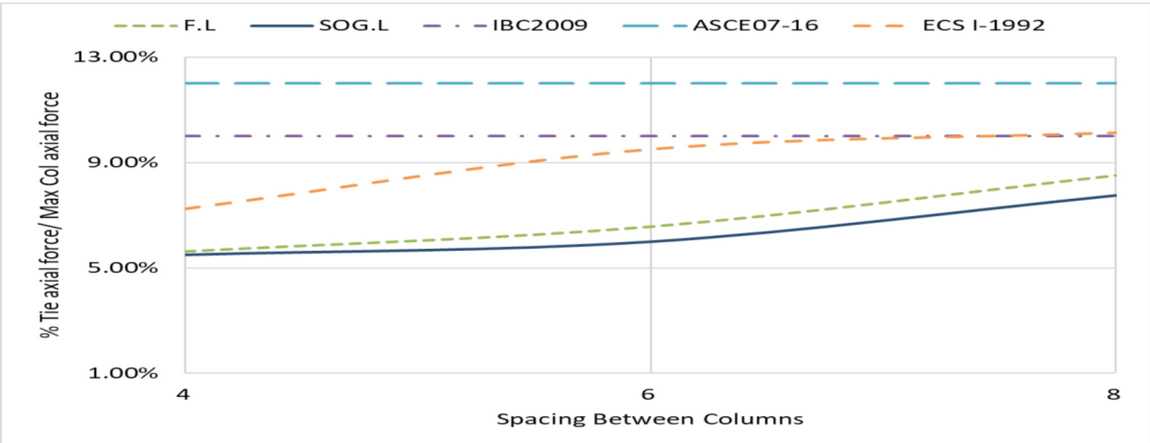

Figure 12: The relationship between the percent Tie axial force / maximum column axial force and the spacing between columns

Figure 12 demonstrates that for all studied framed structures, the ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force increases significantly with the spacing between columns as seismic forces increase with the increase in the weight of the framed structure while the number of columns remains constant. This causes the tie beams' straining actions to increase. Furthermore, the code values for the 3 used codes are higher than the results obtained from the finite element model, and the studied ratio is slightly higher when the tie beams are located in the foundation level than when they are located in the slab on grade level.

4.1.4 The Effect of The Number of Stories

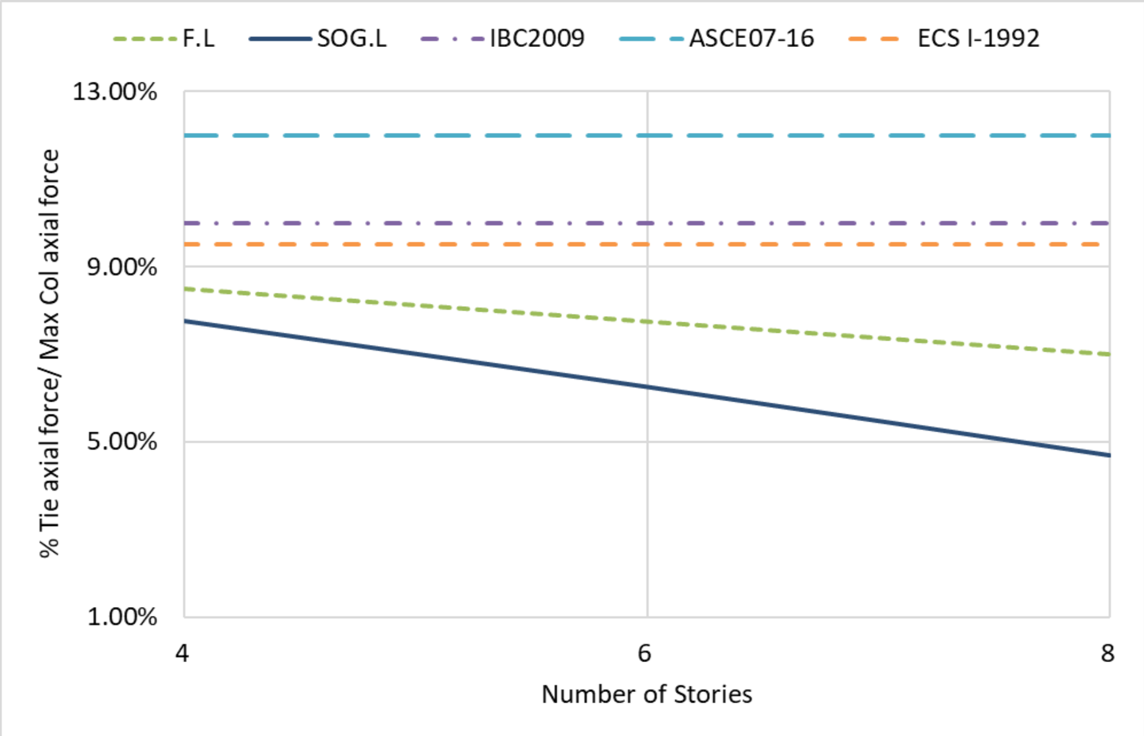

Figure 13: The relationship between the percent Tie axial force / maximum column axial force and the number of stories

Figure 13 shows that the ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force decreases significantly with the number of stories for all studied framed structures as the increase in the compressive force in columns is higher than the increase in the straining action for tie beams. Moreover, the code values for the 3 used codes are higher than the results obtained from the finite element model, and the studied ratio is significantly higher when the tie beams are located in the foundation level than when they are located in the slab on grade level.

4.1.5 The Effect of Tie Beams Cross Section Area

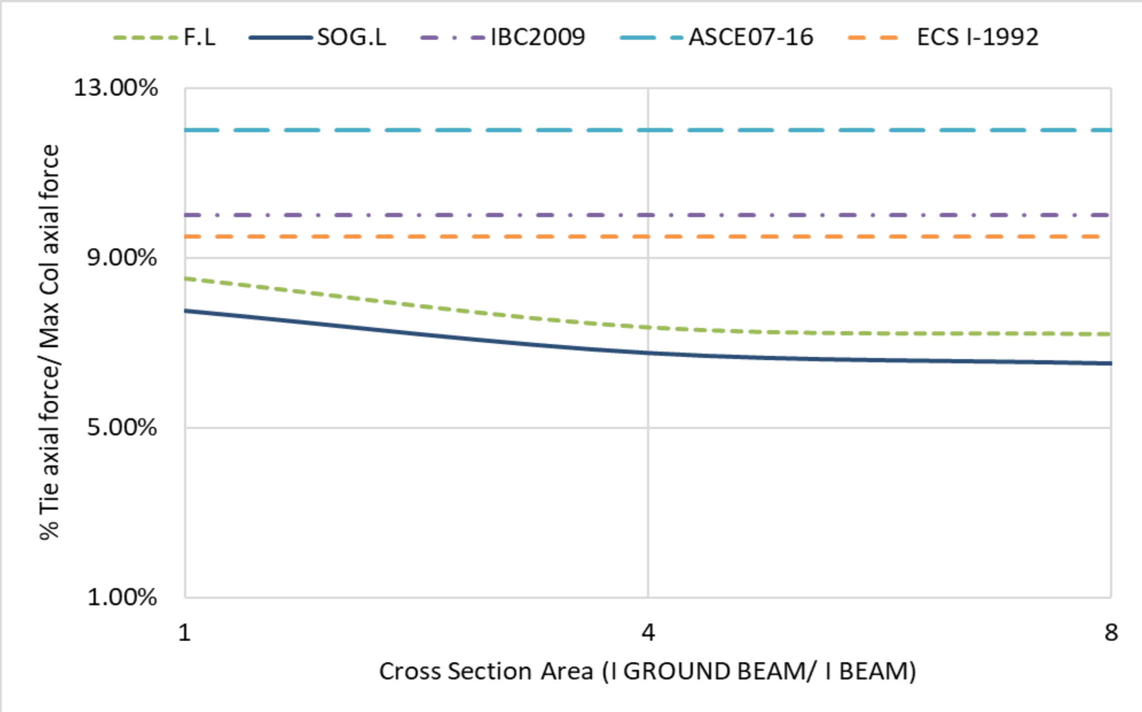

Figure 14: The relationship between the percent Tie axial force / maximum column axial force and tie beams cross section area

Figure 14 shows that the ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force decreases steadily with the tie beams' cross section area for all studied framed structures as the cross section resisting the seismic forces increases. Furthermore, the code values for the 3 used codes are higher than the results obtained from the finite element model, and the studied ratio is slightly higher when the tie beams are located in the foundation level than when they are located in the slab on grade level.

5 Conclusion

The effect of soil structure interaction in the framed structures is investigated in this paper and the results obtained from designing the tie beams are compared with the corresponding code values. Several conclusions are drawn from this parametric study:

[1]. The seismic waves when propagating through different soil types may amplify or diminish according to soil shear modulus, soil density, water content, Plasticity, overconsoildtion and soil thickness. Dense sand tends to amplify the seismic waves, while loose sand and stiff clay tend to diminish the seismic waves.

[2]. The flexible base models (considering the effect of soil structure interaction) have a higher periodic time and relative displacement than the fixed base models, while the fixed base models have a higher base shear than flexible base models.

[3]. The soil structure interaction effect is inversely related with the shear modulus.

[4]. The ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force in columns decreases significantly as the number of stories

increases for all studied framed structures, while the previous ratio is directly related to the shear modulus and the seismic ground acceleration for all studied framed structures.

[5]. The ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force in columns is also inversely related to the cross-section area, as the cross-section area of the tie beam increases, the studied ratio decreases slightly or significantly depending on the span of tie beam and the location of tie beam.

[6]. The most critical case in the studied cases is when the framed structure consists of 4 stories founded on soil type B, the span of tie beams equal 8m, located on foundation level and Iground beam= Ibeam, while the most uncritical case is when the framed structure consists of 8 stories founded on soil type D, the span of tie beams equal 4m, the tie beam is located on SOG level and Iground beam= 8 Ibeam.

[7]. The ratio of the minimum tensile axial force in tie beams to the maximum axial compressive force in columns is lower than the corresponding values from Eurocode 2 (ECS I-1992) [1], American Society of Civil Engineers (ASCE 7-16) [2] or the International Building Code (IBC 2009) [3] in all studied cases.

References

[1]. **European Committee for Standardization (ECS). (2004).** Design provisions for earthquake resistance of structures. Part I: General rules and rules for buildings.

[2]. **American Society of Civil Engineers (ASCE). (2010).** Minimum design loads for buildings and other structures.

[3]. **International building code (IBC). (2009).** Minimum requirements to safeguard the public health, safety and general welfare of the occupants of new and existing buildings and structures.

[4]. **Federal Emergency Management Agency (FEMA),** "A Practical Guide to Soil-Structure Interaction FEMA P-2091," no. December, 2020.

[5]. Computer & Structures inc. structural analysis programs, SAP2000, Computer software package. California: CSI inc. 2005.

[6]. **Xiao Feng Zhang, Harry Far. (2021).** Effects of dynamic soil‑structure interaction on seismic behaviour of high‑rise buildings. Bulletin of earthquake engineering.

[7]. **Meymand PJ (1998)** Shaking table scale model tests of nonlinear soil-pile superstructure interaction in soft clay. PhD thesis in Civil Engineering, University of California, Berkeley.

[8]. **Tabatabaiefar HR, Fatahi B, Samali B (2014)** Numerical and experimental investigations on seismic response of building frames under influence of soil-structure interaction. Adv Struct Eng Int J 17(1):109–130.

[9]. **Liu JB, Du YX, Du XL, Wang ZY, Wu J. (2006).** 3D viscous-spring artificial boundary in time domain. Earthquake Engineering and Engineering Vibration. Volume 5, Issue 1, June 2006, pp. 93–102

[10]. **Fatahi B, Tabatabaiefar HR, Ghabraie K, Zhou WH (2015)** Evaluation of numerical procedures to determine seismic response of structures under influence of soil-structure interaction. Struct Eng Mech 56(1):27–47.

[11]. **Tabatabaiefar HR (2016)** Detail design and construction procedure of laminar soil containers for experimental shaking table tests. Int J Geotech Eng 10(4):328–336.

[12]. **Tabatabaiefar HR, Mansoury B (2016)** Detail design, building and commissioning of tall building structural models for experimental shaking table tests. Struct Des Tall Spec Build 25(8):357–374.

[13]. **H. Bolton Seed, F. ASCE, Robert T. Wong, M. ASCE, I. M. Idriss, M. ASCE, K. Tokimatsu. (1986).** Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils. Journal of Geotechnical Engineering. Volume 112, Issue 11, November 1986.

[14]. **Joseph Sun. R, Golesorkhi, H. B. Seed. (1998).** Dynamic Moduli and Damping Ratios for Cohesive Soils. Journal of Earthquake Engineering. Volume 12, Issue 6, August 1998, pp. 879-913.

[15]. **Egyptian codes for design and construction of buildings. (2018).** Code number 203: Egyptian Code for design and construction of concrete structures.

[16]. **Egyptian codes for design and construction of buildings. (2012).** Code number 201: Egyptian Code for estimating loads and forces in structural and construction works.

[17]. **Abdel-Motaal, M. (1999).** Soil effect on the dynamic behaviour of framed structures. Ph. D. Thesis, Faculty of Engineering, University of Ain Shams, Cairo.