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ASEISMIC CONTROL DEVICE WITH CENTURIES OF APPLICATION EXPERIENCE

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Abstract

The purpose of this study is to demonstrate the applicability of Horasan mortar as a durable friction interface material for natural seismic isolation (NSI) system or device for lightweight building structures with no overturning moment. The NSI system presented in this research was extracted from the historical structures which are in a seismically active zone. The NSI system has been durable against strong earthquake actions for more than ten centuries.

The design presented in this research allows for an economic and safe seismic isolation system design for lightweight structures with no overturning moment. In this research the Design formulations and friction interface area for NSI system were obtained by adding a contact area effect to a Coulomb friction model developed in this research. The results obtained from the NSI system in the presented in this paper show the indirect restoring capability of the earthquake action and its use as a restoring force. The method used to design the seismic isolated structure was obtained by determining the limits of application of the NSI system.

To this end a four-story hospital building with an aseismic device model developed in this research has been selected as an example. For full-scale finite element modelling of the four-story hospital building with NSI system (NSI-Bg) reinforce solid, structural solid and contact finite elements were used in LS-DAYNA software. The governing non-linear equation of motion was modelled as a multi-degree of freedom system with discontinuous and continuous models and solved by adopting direct integration algorithm with the coupling of the control system and system identification toolboxes. As a result of the investigation on the effects of Duzce and Kobe earthquakes in two directions in the plane, the superstructure (under the aseismic isolation device- NSI system) of the building was displaced by an average of between 0.0502 – 0.0923 meter displacement and the earthquake acceleration decreased by an average of 66 % - 63% respectively. On the contrary, the accelerations on the top floor of the fixed-base (FB-Bg) model of the same four-story hospital building increased on average by 16% -29% respectively compared to the earthquake peak ground accelerations. The scaled shake table tests validate numerical results.

The performance of the NSI system indicated its usability in lightweight structures (hospital, school, house etc. up to 4 floors) with no overturning moment. Moreover, the fact that the behaviour of the friction interface of the Horasan mortar as an aseismic material spans centuries gives an important attribute to the NSI system.

Keywords: Natural Seismic Isolation (NSI) System or Device; Earthquake response control; Pure friction seismic isolation; Nonlinear LS-DYNA finite element modelling

1. Introduction

Seismic isolation separates the structure from the harmful motions of the ground by providing the flexibility and energy dissipation capability through the insertion of the isolated device, called isolators, between the foundation and the building structure. Depending on the superstructure and the mass ratio of the base, isolation is classified as base isolation (a standard building with a higher mass ratio) or foundation isolation (a single story building with a lower mass ratio).Tomb of Cyrus (550 BC) is considered the world's first base isolated structure[1].The simplest sliding system is the pure–friction (P-F) system, which does not have any restoring force and a period. It is very effective for a wide range of frequency inputs [2, 3-20].
In order to prevent and control large sliding and residual displacement in the P-F base isolator system, base isolation systems with a restoring force have been developed and investigated [21]. These are mainly period-dependant base isolation systems. The main shortcomings of these isolation systems can be classified as follows [11,12, 14, 18-20]: a) Period dependence; b) Necessity of contact pressure over 10 MPa; c) The behavior has not been adequately studied during successive earthquakes. Seismologists have reported on the vulnerable state of buildings isolated using a period-dependent base isolator against the near-fault pulse ground motions of intra-plate earthquakes or long-period ground motions of inter-plate earthquakes [11,12, 14, 18-20].

The development process of friction base insulation and related friction interface materials is described in references [4-7,9,10,13, 15,19]. As can be seen from these studies, friction interface materials have not been investigated in the repetition interval of major earthquakes. The use Horasan mortar as a friction interface has not been investigated under the effect of earthquake. There is also no references related to the friction coefficient of Horasan mortar. Another important issue is the friction area effect in the frictional isolation system formulated in this study [13], which is not included in the classical Coulomb friction model. The Natural Seismic Isolation (NSI) system, which incorporates the friction interface and friction area interaction, is embedded in Historical buildings. Examples of the seismic isolation system model was discovered for the first time in the Tomb of Cyrus (550 BC) and Walled Obelisk (1204) monuments' [3-7, 9,10,13,15].

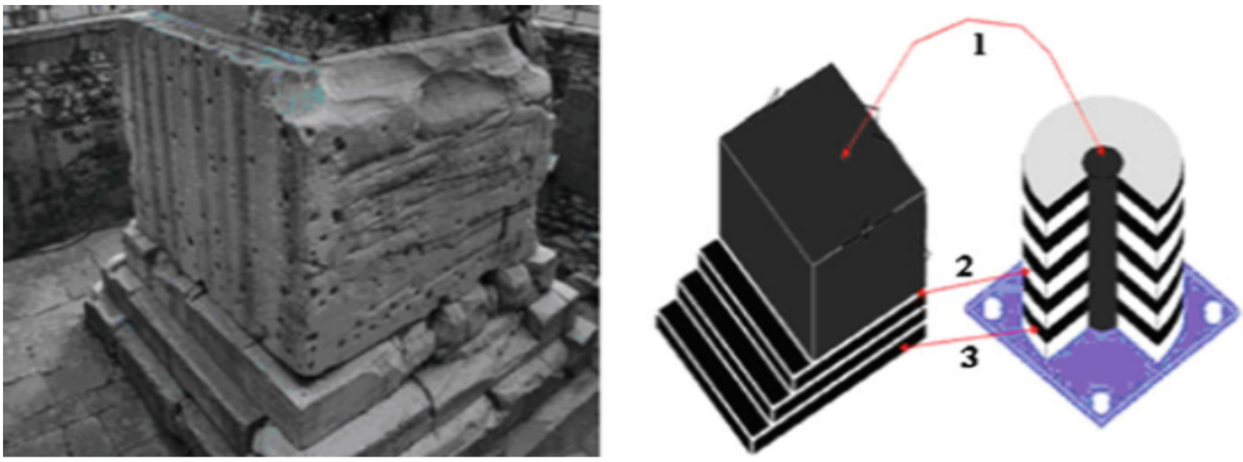


Fig.1. Comparative properties of embedded natural seismic insulation (NSI) system (Walled Obelisk (1204) structure) and the lead core rubber bearing(LCRB) seismic isolation system [5-7].

It is stated that the lower part of the monument consists of three-step marble and one massive marble stone, forming a natural seismic isolation element with four friction / sliding interfaces (Horasan mortar) between the steps and the base. In the schematic in Fig. 1, the following comparisons can be made; the massive marble stone – the lead core damper (1), friction interfaces (Horasan mortar) - rubber (2), the elements that distribute the sliding (marble steps) - hard steel plates (3). Similarly, Tomb of Cyrus monument also contains a natural seismic isolation system consisting of 5 steps. The feasible model of the existing NSI system embedded in historical structures is presented in Fig. 2.

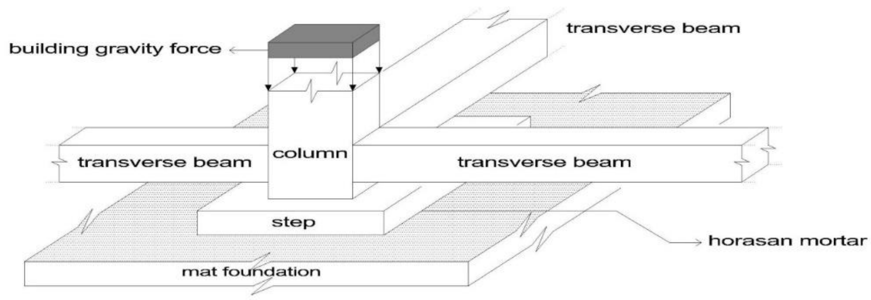


Fig.2 Illustration of the NSI system with single step and single friction interface - Horasan mortar.

In traditional Japanese buildings, the structure-foundation contact design was adopted only with the aim of allowing for natural ventilation below the floor, elevating the wooden parts above the usually damp ground, and preventing rodents and insects from entering the living space. A research carried out [20] explains the structure-foundation contact design of traditional Japanese buildings also had the similar NSI system (device), which allowed them to resist the impact of many earthquakes.

A restoring mechanism is as important of a component of the seismic isolation devices as is stiffness and damping forces in today's rubber bearing seismic isolation devices. Restoring mechanisms in the NSI system also indirectly exist. Mathematical models have been revealed in numerous studies modelling the interaction style of this force [3-7, 9, 10, 15]. It was presented that the earthquake impact force also plays the role as a restoring mechanism. Obtaining the related (static $\mu_s = 0.37$, dynamic $\mu_d = 0.26$,exponential $d_c = 11$) coefficients in the improved Columb friction model for the horasan mortar by minimizing the target function is presented in studies [10,15,19].The aim of this study is to evaluate the performance of lightweight structures that have no overturning moment and are isolated with the NSI system [15,20] under the effect of an earthquake, at least, without the previously mentioned shortcomings.

2 Problem Identification for Application of NSI system

A model of a natural seismic isolation (NSI) system based on the studies presented earlier i.e. an NSI system with a single friction interface consisting of a single reinforced concrete step and Horasan mortar has been created (Fig. 2). By considering earthquake effects a mathematical model and equations of motion for buildings with NSI system are presented. The present investigation explored the feasibility of the application of a structural-mathematical model to the structure-foundation interaction model of lightweight structures with no overturning moment using the NSI system that comprises of a single step and a single sliding interface (i.e. with Horasan mortar) (Fig. 2).

3 Assessment of NSI System for Building Structures

A numerical verification of the building with NSI system (NSI-Bg) is presented with an example of 4 storeys reinforced framed hospital building structure. For comparison the same superstructure with a fixed base (FB-Bg) was considered. The selected building designed using the Turkish Earthquake Building Code (2019) and also meets the requirements of the Private Hospitals Code (2002). The structure consists of 6 axes and 5 spans and has a symmetrical planar geometry along the (x) and (y) axes respectively. The distance between the axes is 7.45m. In the building, there are 36 columns with cross-section dimensions 0.105m x 0.105m on each floor. The cross-sectional dimensions of beams and tie beams are 0.105m x 0.39m. The floors are hollow-tile floor slab with a depth of 0.39m. The floor heights are specified as 4.54 m and 4.1 m for the ground floor and floors above respectively.

A total of 36 reinforced concrete steps with a size of 1.5m x 1.5m x 0.6m are positioned under each column on the ground floor. These reinforced concrete step dimensions were obtained from the study of friction interface area effects in the Coulomb friction model [13]. Under the reinforced concrete steps, 0.02m thick friction interface - Horasan mortar is positioned. Under the Horasan mortar, a mat foundation with 43m x 43m x 0.8m dimensions was designed.The physical and mechanical properties of reinforced concrete, hollow flooring and Horasan mortar are given in Table 2.

Table 1 - The physical and mechanical properties of reinforced concrete, hollow flooring and Horasan mortar

Material	**Reinforced concrete**	**Hollow flooring**	**Horasan mortar**
proporties	C30 Concrete + % 1 reinforcement ratio (S420)		
Elastisite Modülü (N/m^2)	3.8 x 10^{10}	3.8 x 10^{10}	3.89 x 10^{9}
Poisson Oranı	0.25	0.25	0.167
Yoğunluk (kg/m^3)	2400	975	1334.2
Basınç Dayanımı (N/m^2)	0.3 x 10^{8}	0.3 x 10^{8}	0.49 x 10^{7}
Çekme Dayanımı (N/m^2)	0.19 x 10^{7}	0.19 x 10^{7}	1.71 x 10^{6}
Kayma Modülü (N/m^2)	1.52 x 10^{10}	1.52 x 10^{10}	-
Kesme Dayanımı (N/m^2)	-	-	0.275 x 10^{7}
Akma Dayanımı (N/m^2)	-	-	2.745 x 10^{6}
Tang Modu (N/m^2)	-	-	0.235 x 10^{9}

4 Finite Element Modelling and Numerical Study

Numerical modeling and analysis of the structure was carried out with the LS-DYNA (Livermore Software-DYNamic Analisys) software [22] on the basis of the finite element method [17]. The software utilizes the explicit time integration and the analysis can only be performed on fast computers. The structure consisting of mat foundation, Horasan mortar, reinforced concrete steps, columns, beams and floors is modeled with 8-node and 24 degrees of freedom solid finite element type, and the finite elements mesh of the structure is realized in LS-DYNA software .

In the model, 'automatic one-way surface to surface contact finite element type is selected for contact (friction interface) modeling between mat foundation and Horasan mortar and Horasan mortar and reinforced concrete step. Friction interaction is represented by velocity dependant modeling during formulation. In this formulation, related parameters for Horasan mortar were obtained based on references [10,15]. Details of this modeling are schematically illustrated in Figure 3. The finite element model of the structure formed with this arrangement contains 180112 finite elements and 286200 nodes. Nonlinear dynamic analysis of the presented finite element model has been analysed using Duzce and Kobe earthquake's excitations respectively.

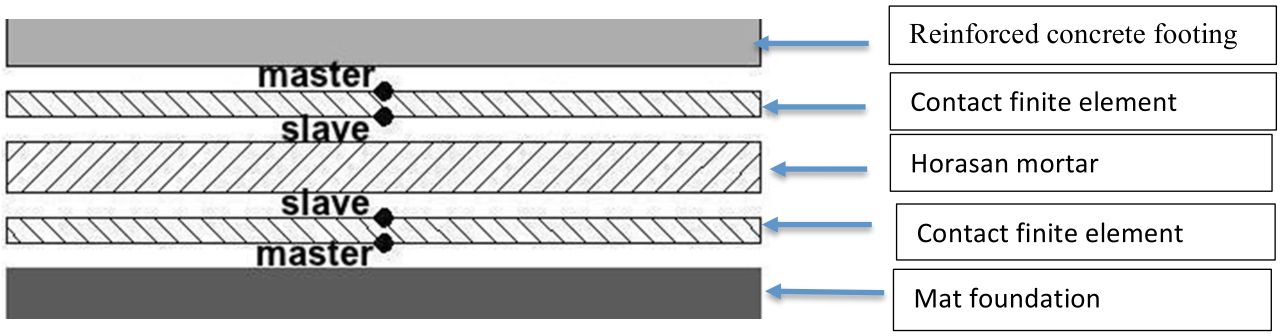


Figure 3. Finite element modeling illustration of Horasan mortar friction interface interaction between mat foundation and reinforced concrete step

General characteristics of these earthquakes are presented in Table 2. The displacement effect of Duzce and Kobe earthquakes introduced to the LS-DYNA software was applied at 0.01 intervals.

Table 2 - Duzce and Kobe earthquakes ground motion characteristics

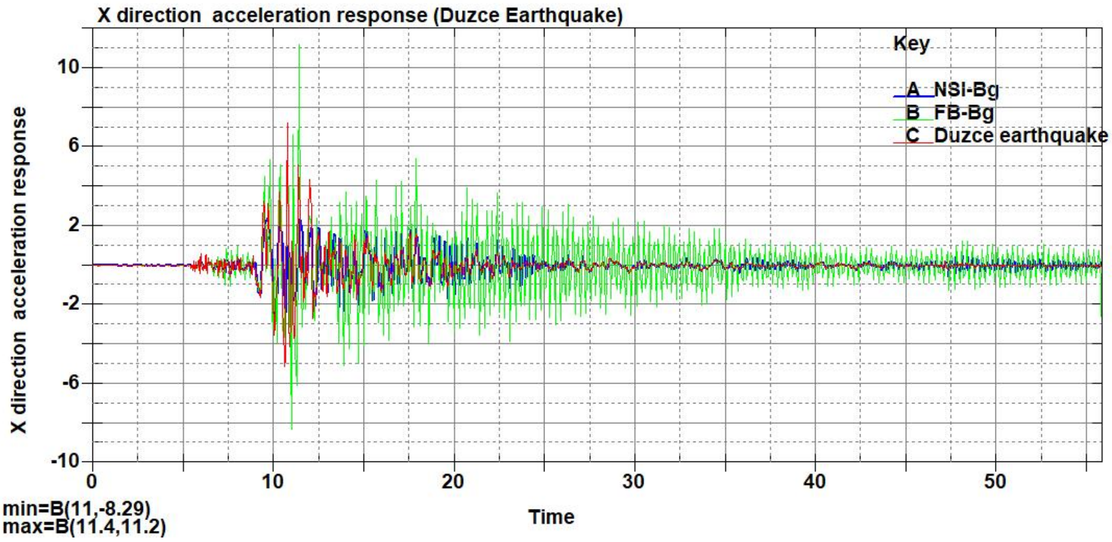
Earthquake	Year	Station	PGA-X (m/sec^2)	PGA-Y (m/sec^2)	Duration time (sec.)	Type
Düzce	1999	Bolu	7.3951	8.0588	55.88	Near fault
Kobe	1995	KJMA	8.1806	6.1704	54.84	Near fault

The dynamic analyses of NSI-Bg structure under the Duzce and Kobe earthquakes excitations are conducted using LS-DYNA explicit solver in the high-speed computer Intel Core i7 4930K @ 3.40 GHz, 2x16 GB RAM @ 1600 MHz. Total CPU time for each analysis are 39 hours 8 minutes 16 second and 50 hours 16 minutes 2 second respectively. Base and top acceleration, velocity, displacement responses for the NSI-Bg and FB-Bg structures under the effect of Duzce earthquakes are provided in Figures 4-6. Their peak values are presented in the Tables 3-5. Von Mises and shear stresses for NSI-Bg nd FB-Bg structures under same excitation are provided in Figures 7-10.

5 Results and Discussion

As presented in Fig.4 the top acceleration response for NSI-Bg structure is tangibly lower than FB-Bg structure and earthquake accelerations respectively. This result came from the building base slipping thanks to the NSI system. Base level peak displacement response (Fig.5) of NSI-Bg structure in X and Y directions are 0.0299 m and 0.0573 m respectively.

The results of the analysis of the NSI system – building structure interaction and FB-Bg structure under the Düzce earthquake excitation show that the acceleration of the NSI-Bg structure decreased by an average of 66.34% ((64.97 + 62.19 + 67.42 + 70.78) / 4) compared to the earthquake acceleration, and the acceleration of the FB-Bg structure increased by an average of 16.43% ((-51.45 + 18.59) / 2). In the isolated structure an average of ((0.0299 + 0.0311) / 2) 0.0305-meter displacement occurred.It is observed that the NSI-Bg structure has an average velocity of ((0.5574+0.53404+0.47922+0.52326)/4) 0.5235m/s and is below the veleocity limit (0.7m/s), while the FB-Bg structure has an average velocity of ((1.5135+0.84232)/2) 1.1779 m/s, and it is observed that it has exceeded the velocity limit.



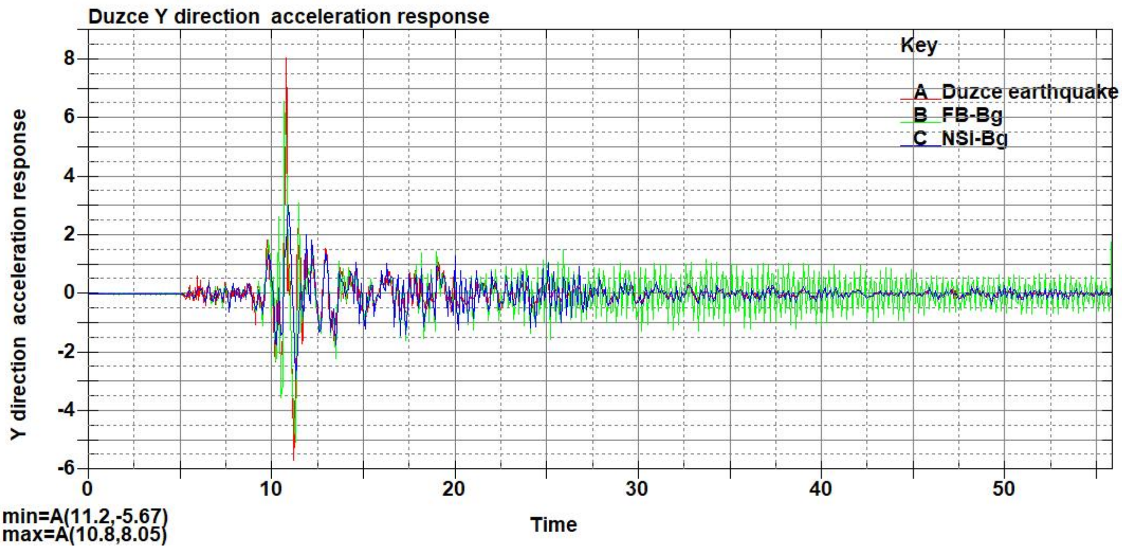
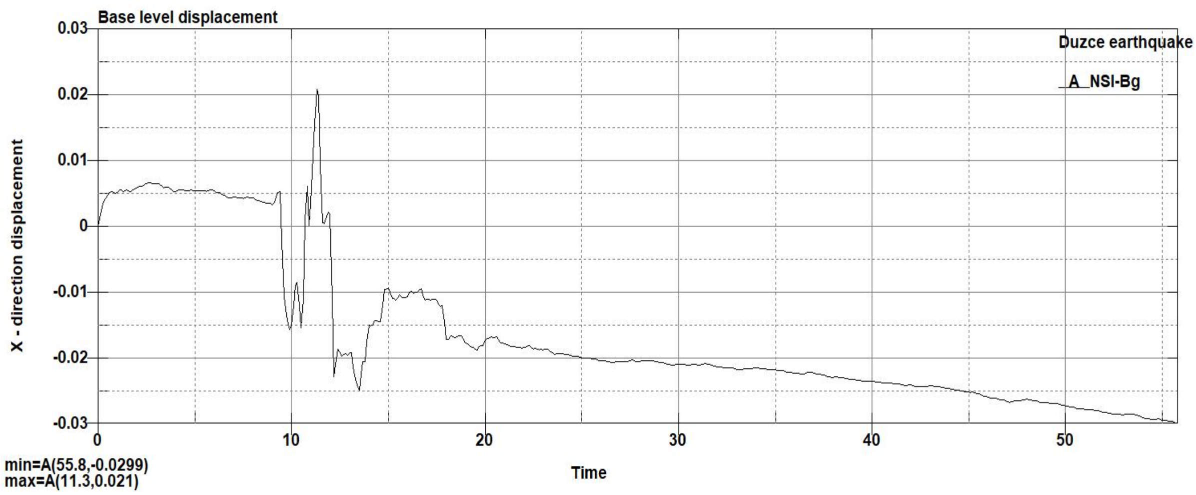


Fig.4 Top storey acceleration response of NSI-Bg (blue) and FB-Bg (green) structures in X and Y directions from the Duzce earthquake excitation (red)



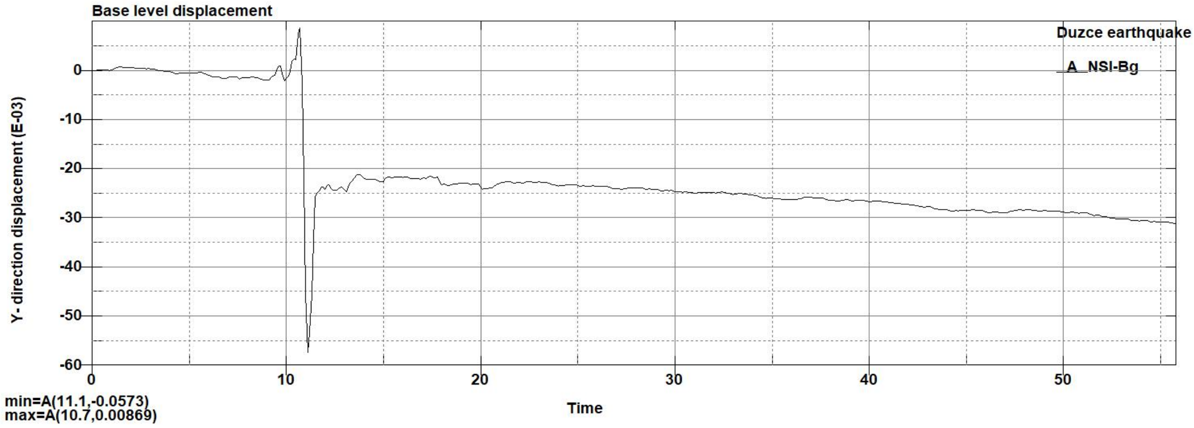


Fig. 5 Base level displacement response of NSI-Bg structure in X and Y directions from the Duzce earthquake excitation

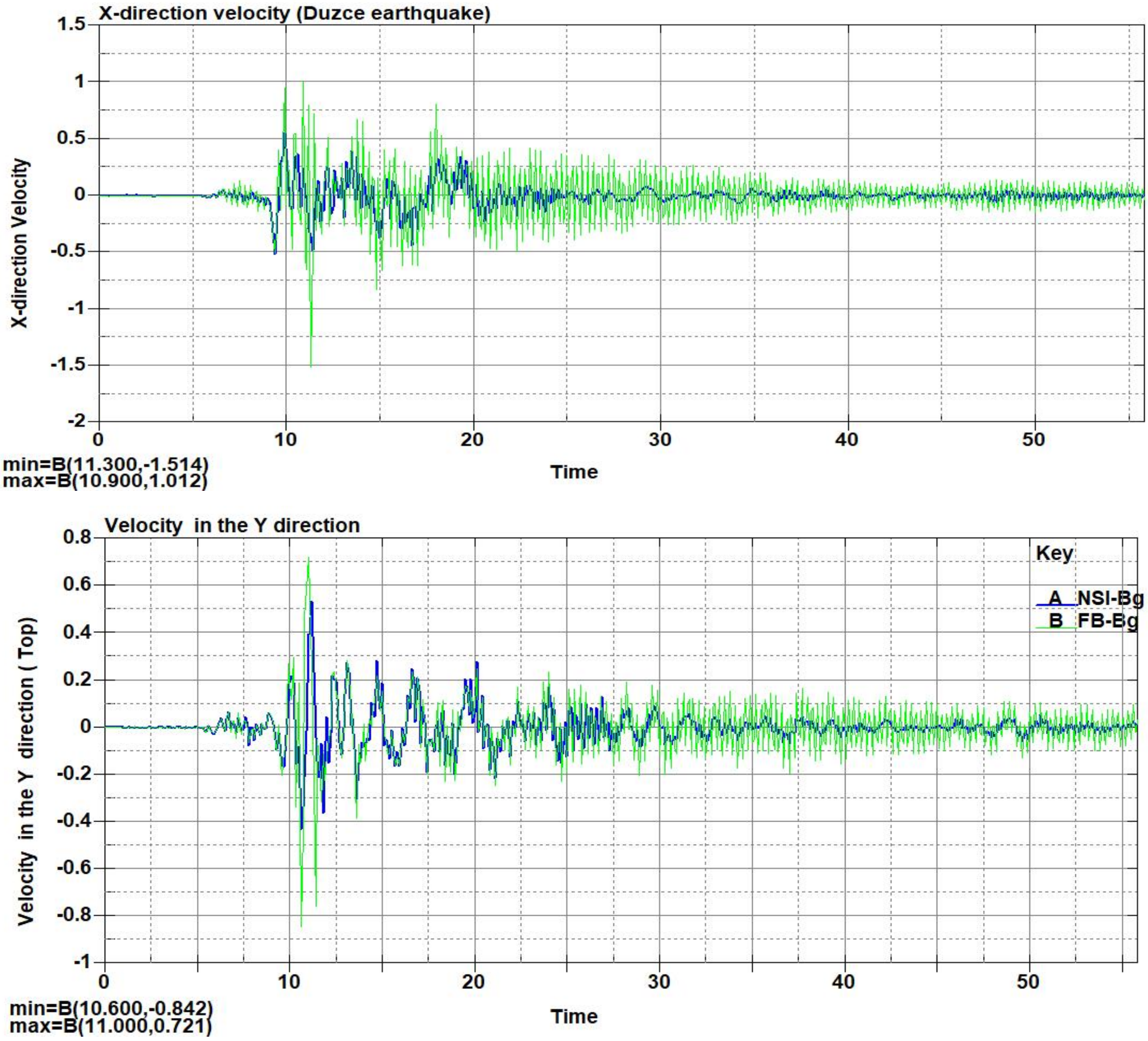


Fig. 6 Top storey velocity responses of NSI-Bg (blue) and FB-Bg (green) structures in X and Y directions from the Duzce earthquake excitation

Table 3 – Base and top-level peak acceleration responses of NSI-Bg and FB-Bg (…) structures from the Duzce and Kobe earthquakes

Duzce earthquake PGA $\ddot{U}$ x = 7.3951 m/s^2 $\ddot{U}$y = 8.0588m/s^2	Accelerations (m/s^2)		Reductions (%)	
Top level	X	Y	X	Y
NSI-Bg, t_{ext}	2.5907,10.1s	3.047,10.9s	64.97	62.19
(FB-Bg, t_{ext})	(11.2,11.4s)	(6.5637,10,7s)	(-51.45)	(18.59)
Base level				
NSI-Bg, t_{ext}	2.422,9.6s	2.354,10.8s	67.42	70.78
Kobe earthquake PGA $\ddot{U}$ x=8.1806 $\ddot{U}$ y =6.1704	Accelerations (m/s^2)		Reductions (%)	
Top level	X	Y	X	Y
NSI-Bg, t_{ext}	2.99,10.4s	2.83,17.1s	63.45	54.13
(FB-Bg, t_{ext})	(12.2,10.9s)	(6.66,10s)	(- 49.13)	(- 7.94)
Base level				
NSI-Bg, t_{ext}	2.54 ,8.6s	2.19,7.7s	68.95	64.51

Table 4 – Base and top-level peak displacement responses of NSI-Bg and FB-Bg (…) structures from the Duzce and Kobe earthquakes

Displacement (m)	**Duzce earthquake PGD** Ux =0.220191 m Uy = 0.1183197 m Displacement (m)		**Kobe earthquake PGD** Ux = 0.18471 Uy =0.17597 Displacement (m)	
Top level	X	Y	X	Y
NSI-Bg, t_{ext}	0.05,55.8s	0.0634,11.1s	0.107,10.7s	0.0593,8.3s
(FB-Bg, t_{ext})	(0.0576,11.4s)	(0.0274 ,10.7)	(0.0564,55.1s)	(0.056,55.1s
Base level				
NSI-Bg, t_{ext}	0.0299,55.8s	0.0573,11.1s	0.118,10.8s	0.0849,8.3s

It is seen that the extremal stresses (Von-Mises and x-y shear stresses) formed in the NSI-Bg structure do not exceed the limit stress values presented in Table 2 of the building materials used. On the other hand, it is seen that these stresses are (5.05/1.021) 4.95 and (6.091/2.41) 2.53 times less than the relevant stresses in FB-Bg structure.Similar results were obtained from the effect of the Kobe earthquake, and the extreme (peak) values of the relevant responses were added to Table 3.4.5.

Table 5 – Base and top-level peak velocity responses of NSI-Bg and FB-Bg (…) structures from the Duzce and Kobe earthquakes

Velocity (m/sec)	**Duzce earthquake PGV** $\dot{U}$ x=0.606372 m/sec $\dot{U}$ y=0.6299939 m/sec Velocity (m/sec)		**Kobe earthquake PGV** $\dot{U}$ x= 0.88818 m/sec $\dot{U}$ y=0.84033 m/sec Velocity (m/sec)	
Top level	X	Y	X	Y
NSI-Bg, t_{ext}	0.5574,9.9s	0.53404,11.2s	0.573,7.5s	0.541,7.5s
(FB-Bg, t_{ext})	(1.5135,11.3s)	(0.84232,10.6s)	(1.51,10.8s)	(1.21,8.6s)
Base level				
NSI-Bg, t_{ext}	0.479,9.9s	0.523,11.1s	0.43,9.8s	0.46 ,7.4

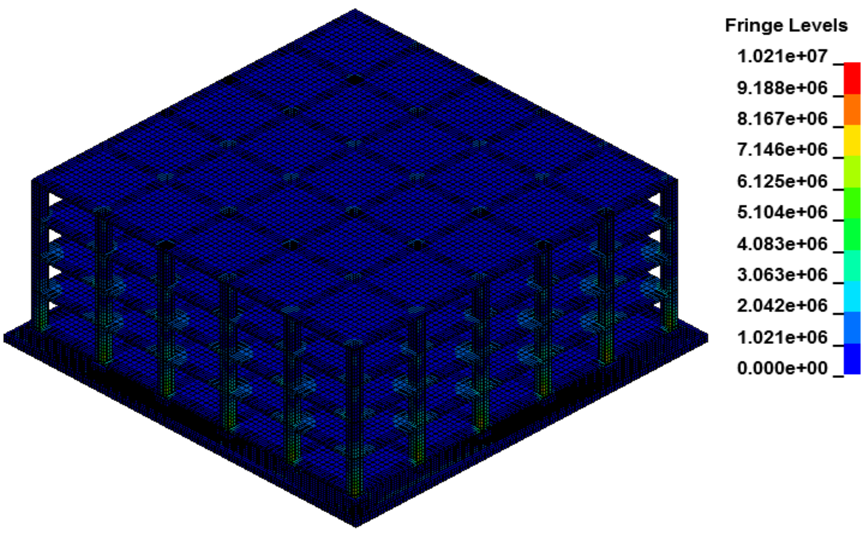


Fig. 7 NSI-Bg structure Von Mises Stress from the Duzce earthquake excitation (for extremum time=11.2 sec)

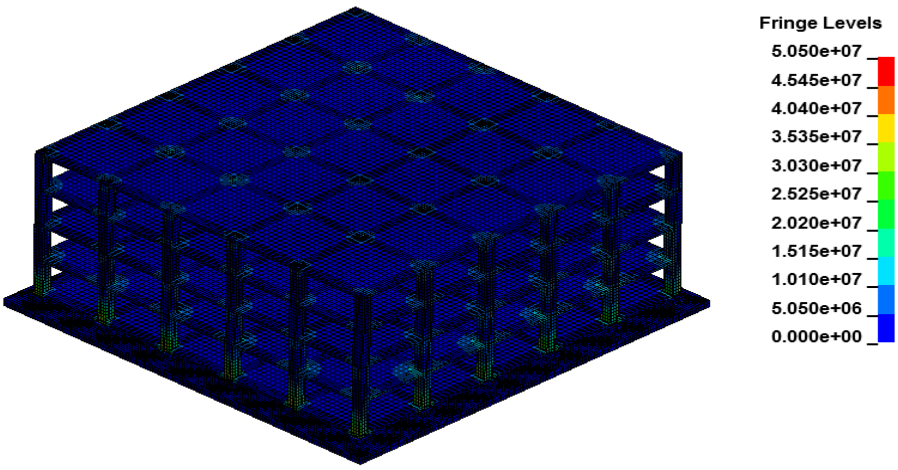


Fig. 8 FB-Bg structure Von Mises Stress from the Duzce earthquake excitation (for extremum time= 11.4 sec)

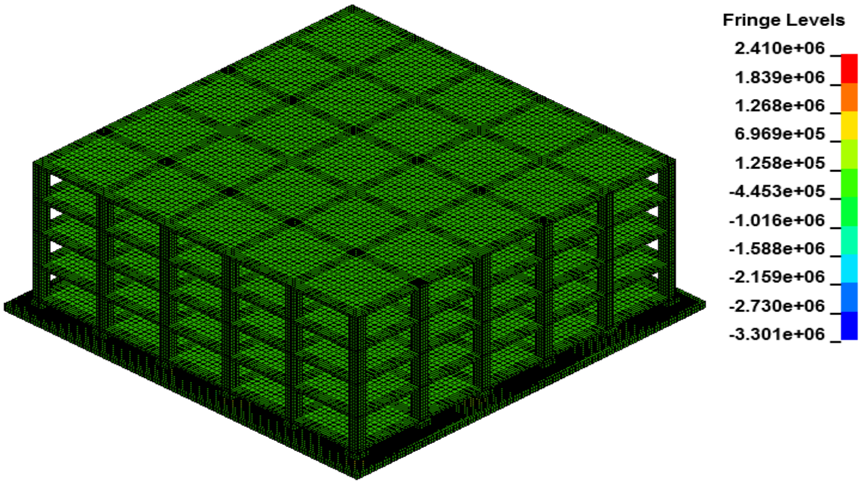


Fig. 9 NSI-Bg structure Shear Stress from the Duzce earthquake excitation (for extremum time= 55.83 sec)

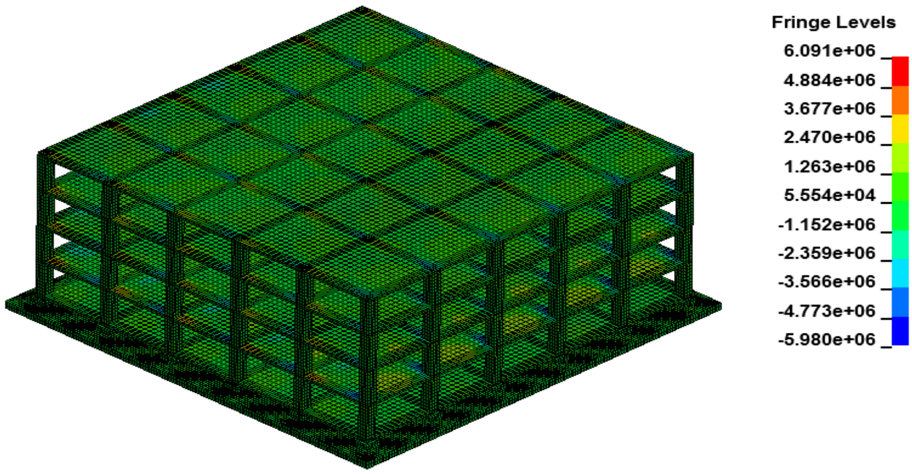


Fig. 10 FB-Bg structure Shear Stress from the Duzce earthquake excitation (for extremum time= 11.4 sec)

6. Conclusions

In this study, the following concrete results were obtained and the related suggestions are presented below:

1) A mathematical model of the embedded Natural Seismic Isolation (NSI) system found under the previously mentioned historical structures that have survived in strong earthquake zones was formulated, 3-6]; the repetition interval of major earthquakes

2) Horasan mortar's aseismic characteristics which are historically tested and proven to be effective under repetitive earthquakes experienced throughout the structures existence, was used as a friction interface in the NSI system [3, 19].

3) Design formulations and methods are obtained by adding area effect to Coulomb friction model developed for NSI system's friction interface step area design [13];

4) It has been observed that the earthquake force acting on the NSI system also provides the restoring force mechanism [9, 10];

5) In order for the friction interface (Horasan mortar) used in the developed Coulomb friction model for NSI system, to more accurately reflect the friction interaction behavior, the method of finding relevant parameters (μ_s, μ_d, d_c) is based on experiments as presented [10, 15];

6) Seismic isolated structure design method for using the NSI system is given and application limits are determined [15];
7) In earthquakes with magnitude greater than 6, the lightweight FB-Bg structures (i.e. that exhibit no overturning moment) were shown to increase the base acceleration by an average of 44% and it was shown that these structures can only be safely used with seismic isolation.

In the presented examples, the NSI system has been shown to perform well, and summary details are summarized below:
a) As known from the related building codes, for earthquake effects up to 6 magnitude, structures without any seismic isolation system expected to survive. Therefore, the application and design of the NSI system is designed in such a way that the foundation of the building can provide fixed base behavior in earthquakes up to 6 magnitudes;
b) In the case of Düzce (7.3951, 8.0588 m/s^2) and Kobe (8.1806, 6.1704 m/s^2) earthquakes with a magnitude greater than 6, the structure has been displaced in the range of 0.0299m – 0.118m and the acceleration range has been obtained as 2.1976 m/s^2 –3.0472 m/s^2, and the earthquake acceleration has decreased by 54.13% - 70.78% respectively;
c) It was observed that the speed and stress values did not exceed the relevant limit values;

The NSI System's features and reducing the earthquake acceleration in the sample applications by 54% to 71%, and the fact that the speed and stresses did not exceed the relevant limit values brought the following suggestions:

- It can be used in lightweight (up to 4 floors hospital, school, residential etc.) structures with no overturning moment;
- Since the design and implementation of the NSI system is very economical, it provides an opportunity for wide use;
- The fact that the behavior of the friction interface (Horasan mortar) used in the NSI System has been historically tested for centuries, gives the NSI system an important attribute;

7. Acknowledgements

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