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A new seismic isolation system: sleeved-pile with soil-rubber mixture

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Abstract

To increase the safety of structures against strong ground motions and their life due to environmental issues on the earth and saving in terms of materials, it is necessary to expand and upgrade seismic resistant systems. However, more cost-effective systems which have sufficient influence on the seismic performance of structures and also more compatibility with the regional conditions, will be more desirable than other systems. One of the seismic resistance systems is seismic isolation. In the event of interest in using the seismic isolation system for a mounted building on piles, the costly construction of piles and isolation equipment shall be provided simultaneously. The seismic isolating using sleeved-piles which is generally used in combination with various damper systems, can help to overcome this issue. In this research a seismic isolator system using sleeved-pile has been studied while considering the damping behavior of the soil-rubber mixture as the only source of damping. To investigate the proposed system, a series of tests including static lateral load test, dynamic free and forced vibration tests, were performed on a model pile in a field laboratory which has been constructed for this purpose. According to results of tests the proposed system has a good deformation ability and damping characteristics, and as a method of seismic isolation is completely efficient.

Keywords: *Seismic isolation, Sleeved pile, Soil-rubber Mixture.*

1. Introduction

To increase the safety of structures against strong ground motions and their life due to environmental issues on the earth and saving in terms of materials, it is necessary to expand and upgrade seismic resistant systems. Nowadays the seismic isolation is widely used as a developed technology in many earthquake-prone regions of the world to protect important structures from strong earthquakes [1]. However, more cost-effective systems which have sufficient influence on the seismic performance of structures and also more compatibility with the regional conditions, will be more desirable than other systems. In some situations it is necessary to use deep piles in order to fulfill requirements of bearing capacity, settlement, sliding, overturning and also uplift. In the event of interest in using the seismic isolation system for such buildings, the costly construction of piles and isolation equipment shall be provided simultaneously.

Of the seismic isolation systems, the seismic isolating using sleeved-piles is generally used in combination with various damper systems. In this isolation system the piles are made flexible by being enclosed in pipes with a suitable gap for clearance [1].

Due to low horizontal stiffness between the structure and the foundation, the structure will be decoupled from the horizontal components of the ground motion. This isolation system does not absorb the earthquake energy, but rather deflects it through the dynamics of itself. Although this effect does not depend on damping, a certain level of damping is beneficial to suppress possible resonance [1].

2. Proposed Seismic Isolation System

According to available data in the literature, sleeved-pile isolation system was implemented in the Union House in Auckland, New Zealand, (completed in 1983), Wellington Central Police building (completed in 1991) and Randolf Langenbach house in Oakland, California (completed in 1998) [1]. In all these structures the horizontal stiffness is reduced by sleeving piles (primary demand of a seismic isolation system) and the required damping is provided by placing a damping system between the structure and the ground (the other seismic isolation system requirement), Fig. **1**. The Union House, as the one of the earliest base isolation projects, is located in an area of poor soil and mounted on 10 m piles which are enclosed by steel sleeves with a clearance of 150 mm. The needed damping is provided by the elastic-plastic deformation of a set of tapered steel plates arranged around the perimeter of the building at ground level [2]. The Wellington Central Police Station is supported on 15 m sleeved piles with a clearance of 375 mm [3]. Damping

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in this structure is provided by 24 lead extrusion dampers [4]. The developer of seismic isolation for the Randolf Langenbach house is the owner of it. Damping in this building is provided by hydraulic viscous dampers, and also a rubber bumper system as an additional damping source [1].

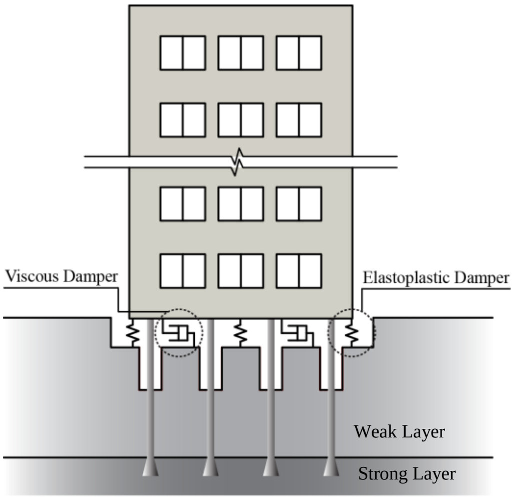


Fig. 1 Seismic Isolation System Using Sleeved-Piles in Combination with Various Damper Systems

Ishimaru et al. has conducted studies on sleeved piles system to evaluate the feasibility of construction of seismic base-isolation on soft ground sites. They performed two set of tests on sleeved piles, one (1991) included four 6.2 m plies which were sleeved at the top 2 m of them with a larger pipe and supporting a 1.8*1.8*2 m^3 concrete block [5], and the other set (2004) included a real size seismic-isolation system in which a 20*15 m^2 concrete slab was supported on four 36 m sleeved piles (the sleeve pipe height was 7 m) [6]. They used three different types of dampers in their tests and compared the results with the case that no damper in the test setup. They observed that the sleeved-pile isolation system can produce a damping force without implementing any additional damping system [5]. However, because of the decreased stiffness of the relying system on the piles, a need to a damper to prevent unwanted deformation and resonance occurrence seems necessary.

In this research a seismic isolator system using sleeved-pile has been studied while considering the damping behavior of the soil-rubber mixture as the only source of damping. Experimental evidences show that some energy is dissipated even at very low strain levels, so the damping ratio in soils is never zero [7]. The damping behavior of soils varies by plasticity characteristics [8], [9], [10]. Damping ratios of highly plastic soils are lower than those of low plasticity soils at the same cyclic strain amplitude [7]. The authors' proposed isolation system includes a sleeved-pile in which the annular space between the pile and the sleeve is filled with a mixture material according to Fig. **2**.

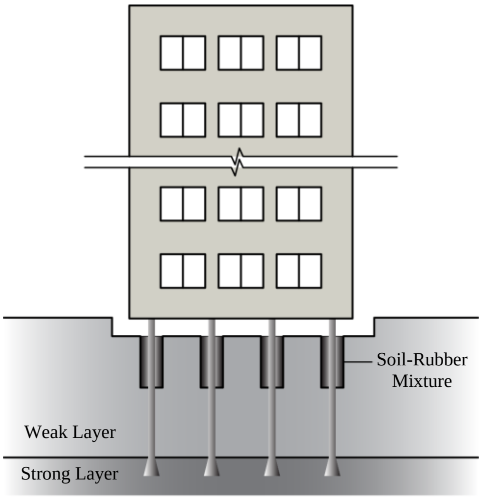


Fig. 2 Proposed Seismic Isolation System, Sleeved-Piles with Soil-Rubber Mixture

This mixture was studied by Komakpanah and Mahmudi (2012) and is containing Firuzkuh 161 sand (a low plasticity soil) and rubber particles. As the rubber particles decrease the mixture shear modulus, it could be expected that the horizontal stiffness of a conventional pile system will be decreased by filling the sleeved part of the pile with soil-rubber mixture. Hence the system can perform as a seismic isolation system. Due to inherent damping characteristics of soil and energy absorbing ability of rubber particles, applying soil-rubber mixture can provide sufficient damping which leads to no need to additional damping equipment. Fig. **3** shows the maximum strain versus rubber weighted percentage according to Komakpanah and Mahmudi study. Area marked by the ellipse in this Figure defines the transition zone between the sand dominant behavior and the rubber. Weighted percentage of rubber particles of the used mixture in this study is considered 20% which is almost from the first points of the transition zone. Rubber particles size is between 2 and 3 mm, and the mixture density is 1.198 gr/cm^3. Table 1 shows a simple comparison between existing sleeved pile seismic isolation systems and the proposed system in this article.

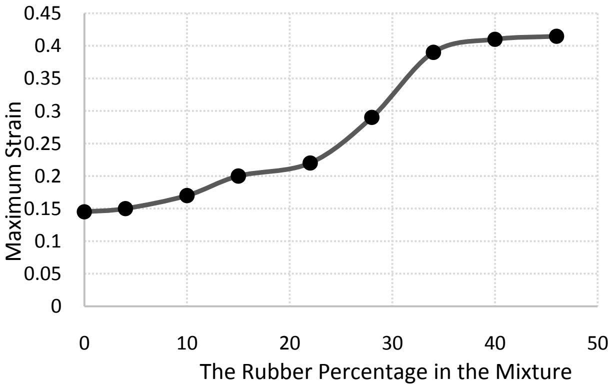


Fig. 3 Maximum Strain versus Rubber Weighted Percentage [11]

Table 1 Comparison between existing sleeved pile seismic isolation systems and the proposed system in this article

Sleeve Pile Isolation System used in	Damping Source
Union House	elastic-plastic deformation of a set of tapered steel plates
Wellington Central Police building	lead extrusion dampers
Randolf Langenbach house	hydraulic viscous dampers + A rubber bumper system
Ishimaru et al.	Lead damper
	Typical friction damper
	Double friction damper
	No Damper
Proposed System in this Article	Soil-Rubber Mixture

3. Test Models

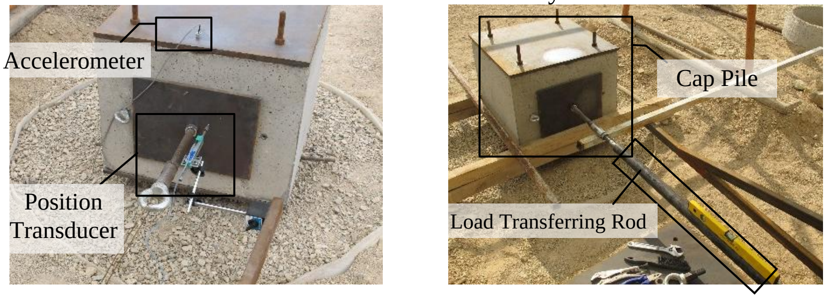
To evaluate the proposed system, a series of field laboratory tests were performed on a model pile in a field laboratory which has been constructed for this purpose (Fig. **4**).

These tests include static lateral load test, dynamic free and forced vibration tests. Each test has been performed on three different models; *Con Model*, a conventional pile system, *Iso Model*, sleeved-pile system with an empty annular space between pile and sleeve and *Iso_M Model*, a sleeved-pile system while the annular space between the pile and the sleeve is filled with soil-rubber mixture.

a. Field Laboratory Facility

b. Pile Model

c. Hydraulic Power Pack



d. Instrumentation, Position Transducer and Accelerometer

e. Test Setup

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f. Instrumentation, Load Cell g. Hydraulic Double Action Cylinder

Fig. 4 The Constructed Field Laboratory Facility to Assess the Proposed System

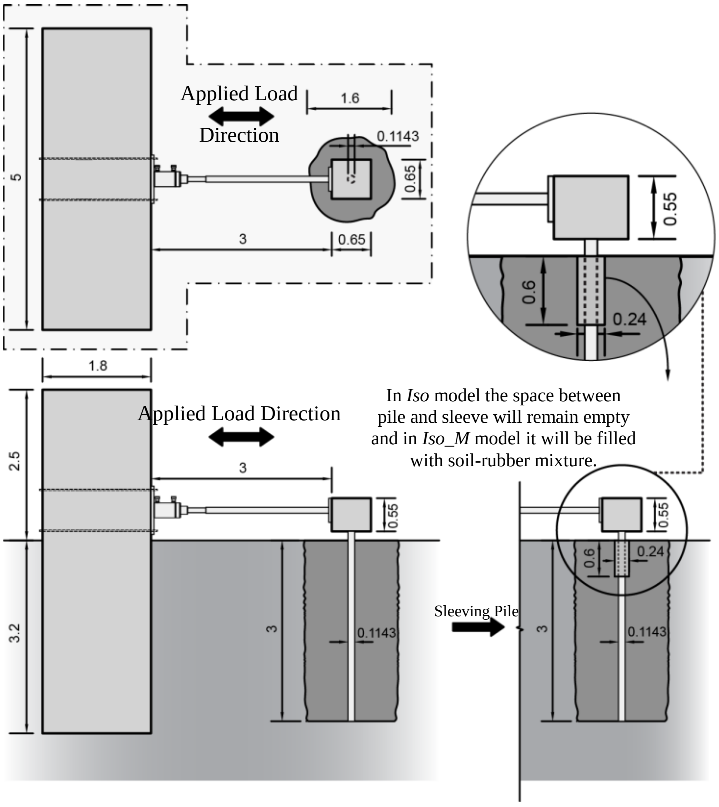
4. Tests Description

The performed tests program is presented in Table 2.

Table 2 Tests Program

No.	Model Name	Test Type	Test Name
1	Con	Static Load Test	St_Con
2	Con	Free Vibration Test	DyFr_Con
3	Con	Forced Vibration Test	DyFo_Con
4	Iso	Static Load Test	St_Iso
5	Iso	Free Vibration Test	DyFr_Iso
6	Iso	Forced Vibration Test	DyFo_Iso
7	Iso_M	Static Load Test	St_Iso_M
8	Iso_M	Free Vibration Test	DyFr_Iso_M
9	Iso_M	Forced Vibration Test	DyFo_Iso_M

In these experiments, the compressive and tensile lateral load is applied to the cap pile by a double action hydraulic jack. For a better understanding of the tests, dimensions and arrangement of model elements are shown in Fig. **5**. As specified in this Figure, a shaft of 1.6 m diameter (more than 8 times of pile diameter) is excavated and the pile is placed vertically at the center. According to the volume of the drilled shaft and the pile dimensions, the required soil weight is calculated and with a suitable method filled around the pile to achieve the desired density. The particle size analysis curve of this soil and its properties are shown in Fig. **6** and Table 3, respectively. Having filled the shaft, the pile cap is fixed to the pile and connected to the mounted hydraulic cylinder on the reaction wall using an appropriate load transfer tool.



In *Iso* model the space between pile and sleeve will remain empty and in *Iso_M* model it will be filled with soil-rubber mixture.

Fig. 5 Test Arrangement and Dimensions for Con, Iso and Iso_M Models (Dimensions according to m)

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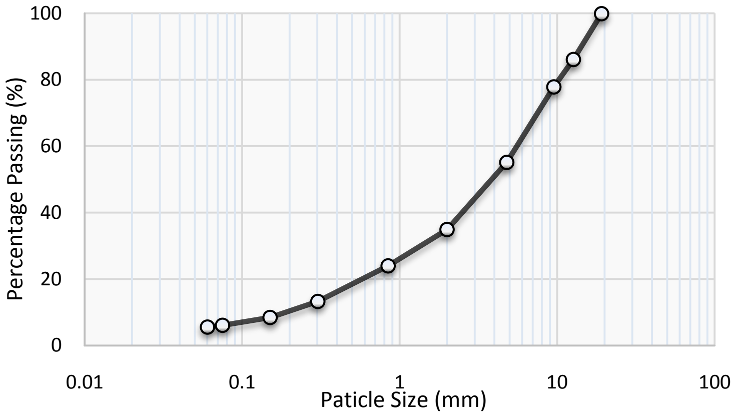
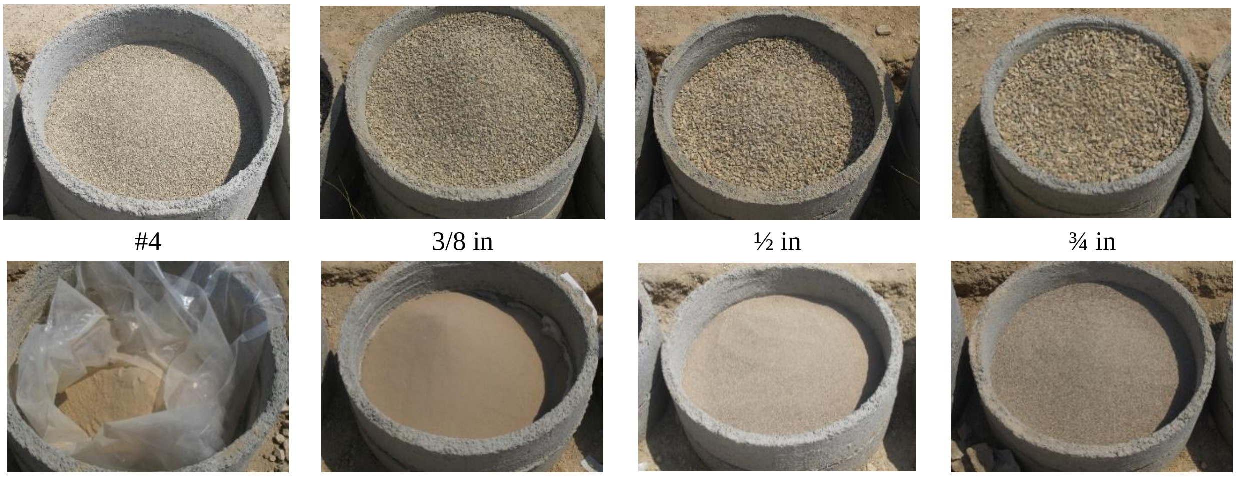


Fig. 6 Particle Size Analysis Curve of Soil around the Pile

Table 3 Model Soil Properties

Parameter	Unit	Value
γ_m	Kgf/m^3	1690
e_m	–	0.543
D_r	–	0.19
Slope of SSL (α)	–	0.039

Fig. 8 shows the connection details between the cap pile, pile and load transfer device. The properties of aluminum model pile and concrete cap pile is presented in Table 4.



#4 3/8 in ½ in ¾ in

#100 #50 #20 #10

Fig. 7 The Used Soil Grains to Build the Soil Model According to Fig. **6**

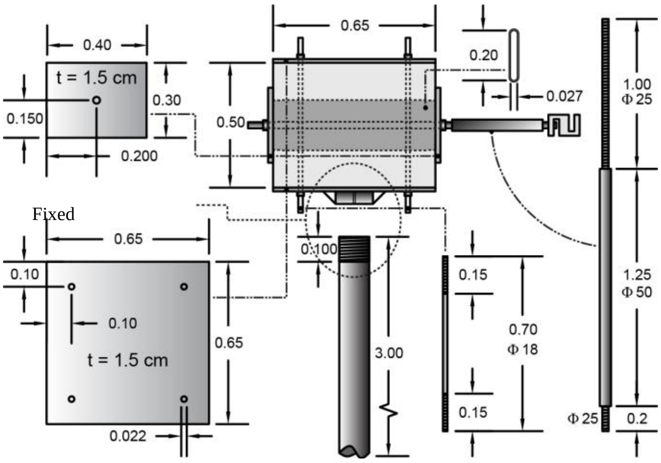


Fig. 8 Cap Pile, Pile and Load Transfer Device for Connection Detailing

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Table 4 Model Pile and Cap Pile Properties

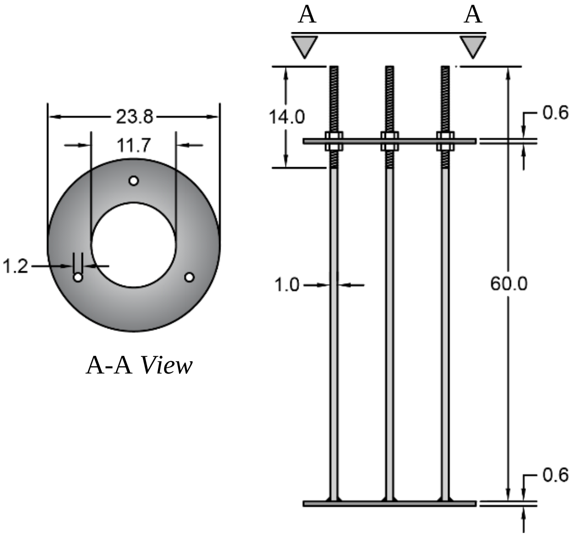
Material	Parameter	Unit	Value
Aluminum Pile	L, length	m	3
	B, Outer Diameter	m	0.115
	t, Thickness	m	0.004
	EI, Flexural Stiffness	$Kgf \cdot m^2$	1.363e4
	γ_{Al}	Kgf/m^3	2700
Concrete Cap Pile	Dimension	m	0.55*0.65*0.65
	γ_{Conc}	Kgf/m^3	2400

5. Sleeved-Pile Model construction

To construct sleeved-pile system, about 0.6 m from top of the *Con* model is excavated and after putting the sleeve around the pile (with the aid of template, Fig. **9**-a), the sleeve is backfilled with the excavated soil at the considered density (Fig. **9**-b). For construction of *Iso_M* model, the soil-rubber mixture is prepared with regards to its density and the volume between the pile and the sleeve, and is placed at that annular space with a suitable method to obtain the desired density (Fig. **10**).

a. Excavation of 0.6 m of top of the Con model

b. backfilling the sleeve with the excavated soil at the considered density



c. The Used Template for Pile Sleeving

Fig. 9 Constructing Iso Model

Fig. 10 Preparing the Soil-Rubber Mixture and Constructing Iso_M Model

6. Tests and Test Results

6.1. Static lateral loading tests (compressive and tensile)

In these tests the lateral compressive and tensile load is applied gradually to the cap pile by a double action hydraulic jack. In all three models the compressive load is increased to 100 kgf followed by unloading and reloading

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to a tensile load of 100 kgf. In the next steps of loading the load value is increased to 200, 300 and 400 kgf for each cycle and only in *Con* model it reached to 460 kgf. The load-displacement curves for each model are shown in Fig. **11**. The dash-dot line in this Figure shows the linear load-displacement relation. The horizontal stiffness of *Con* model, *Iso* model and *Iso_M* model are 53.878, 14.86 and 29.004 kgf/mm, respectively. It should be noted that to achieve softer systems, one can use taller sleeves or soil-rubber mixtures with higher percentages of rubber particles.

As seen in this Figure due to sleeving the first 0.6 m of the pile, system stiffness has decreased considerably in the *Iso* model.

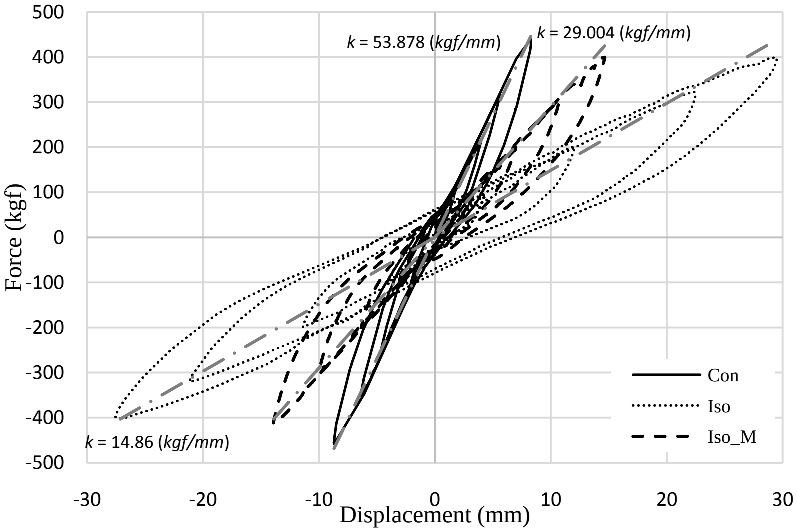

Fig. 11 Load-Displacement Curves for Static Loading Tests

6.2. Free vibration tests

To perform these tests, the applied traction to the cap pile is released suddenly and system starts to vibrate. The tests were conducted presuming the initial displacement of 1.6 mm for *Con* model, 4.7 mm for *Iso* model and 3.7 mm for *Iso_M* model. Fig. **12** shows normalized displacement responses of the cap pile to the initial displacement (X_0). Based on the recorded waveform and the logarithmic decrement, it is possible to calculate the natural period of vibration and the amount of viscous damping (ξ). The damping can be calculated from Equation 1 for systems with damping less than 20% ($\omega_d \cong \omega_n$) [12].

$$\xi = \frac{ln\frac{a_i}{a_j}}{\pi(j-i)} \tag{1}$$

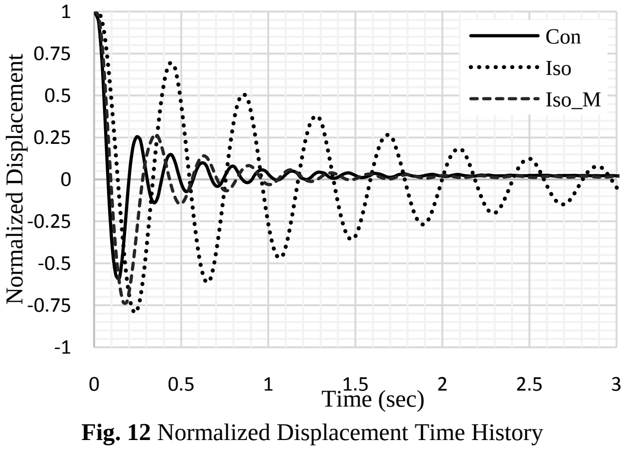

Fig. 12 Normalized Displacement Time History

Where a_i and a_j are response amplitude for i and j cycle of vibration. The calculated values of natural period and viscous damping according to the test results are presented in Table 5.

Table 5 Period and Viscous Damping Values from free Vibration Test Results

Model	T (sec), Period	ξ, Viscous Damping
Con	0.18	0.16
Iso	0.42	0.11
Iso_M	0.27	0.18

The results of analytical studies of Shimomura et al. that approximates the influence of system damping as viscous damping, are in a good agreement with the measured one from the free vibration test on sleeved-pile system [13]. Therefore, the obtained values from these test results can be taken as an accurate estimate of the system's damping. It is obvious from Table 5 that the natural period is increased by 50% in *Iso_M* model rather than *Con* model and there is also a good amount of damping has been presented in *Iso_M* model. On the other hand Fig. **12** reveals that, although the initial displacement in *Iso_M* model is more than its value in *Con* model but the residual displacement in *Iso_M* model is less than its counterpart in *Con* model. This could be a result of the presence of rubber particles and the restoring force produced by them that lead the system to its initial position.

6.3. Dynamic Forced vibration Tests

Hydraulic loading equipment used in these experiments is able to apply a triangular cyclic load with a given

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displacement amplitude and frequency, so it is possible to apply cyclic load to the cap pile using the mounted hydraulic jack on the reaction wall by the means of a loading rod. As it is expected, the forces applied to the isolated structure is less than the applied forces to the conventional structures, the dynamic load applied to the *Iso* and *Iso_M* models is less than the applied load to the *Con* model. The input vibration displacement amplitude for *Con*, *Iso* and *Iso_M* models are 1.75, 3.2 and 2.2 mm, respectively, and the loading frequency is 1 Hz. The time history of the applied displacement to the cap pile is shown in Fig. **13** (a, displacement amplitude). To ensure reaching a steady state of load-displacement, 18 cycles of loading and unloading is performed.

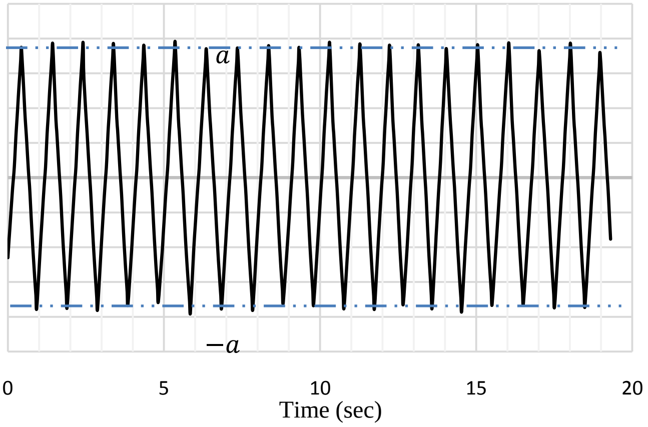

Fig. 13 Time History of the Applied Displacement to the Cap Pile

The load-displacement curves for each model is shown in Fig. **14**. The horizontal cyclic stiffness of *Con*, *Iso* and *Iso_M* models are 47.794, 17.515 and 27.5 kgf/mm, respectively. According to the hysteresis loops (wasted energy) and the strain energy per cycle, the equivalent viscous damping can be calculated using Equation 2 [12].

$$\xi_{eq} = \frac{1}{4\pi}\frac{1}{\omega/\omega_n}\frac{E_D}{E_{S0}} \tag{2}$$

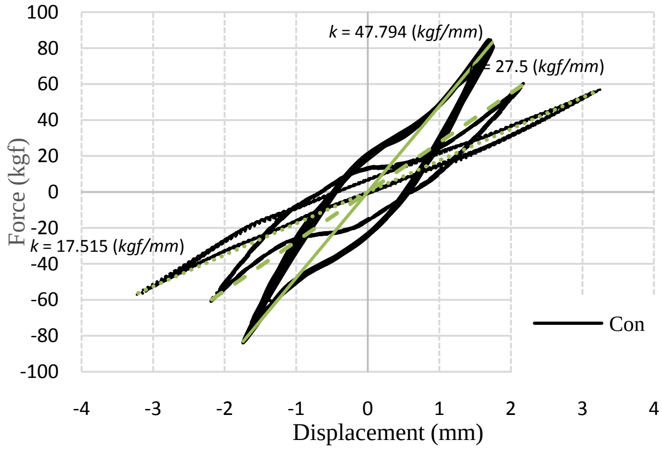

Fig. 14 Load-Displacement Curves for Dynamic Forced Vibration Tests

Where ω = loading frequency, ω_n = natural frequency of system, E_D = dissipated energy per cycle (the area of a closed loop) and E_{S0} = strain energy. Strain energy in this Equation can be calculated by $E_{S0} = ka^2/2$ (k and a are linear stiffness and displacement amplitude) [12]. Equivalent viscous damping values for each model based on the largest hysteresis loop are presented in Table 6.

Table 6 Equivalent Viscous Damping values from Dynamic Forced Vibration Test Results

Model	Equivalent Viscous Damping
Con	0.771
Iso	0.088
Iso_M	0.349

It can be seen in Fig. **14** that sleeving of the pile (*Iso* model), decreases the system stiffness and also damping as a result of reducing the horizontal stiffness of pile due to removing surrounding soil at the top of it and accordingly increases the system sensitivity to lateral forces. Regard to the test results on the *Iso_M* model, the system stiffness is reduced and also an appropriate amount of damping is introduced to the system. For the Union House the main period of vibration of the sleeved-piles system is around 4 sec. The used dampers in this building provide elastic stiffness in addition to damping and reduce the period to around 2 sec [14]. According to the test results such a situation arises in the *Iso_M* model compared to the *Iso* model. However, the *Iso_M* model has an acceptable function.

7. Conclusion

According to results of static and dynamic tests, it is observed that;

- A sleeved-pile system with soil-rubber mixture is quite effective in prolonging the period, so the primary demand of a seismic isolation system is achieved.
- The used soil-rubber mixture, introduced sufficient damping to the system due to inherent damping characteristics of soil and energy absorbing ability of rubber particles, so the other important requirement for a seismic isolation system is obtained.
- A restoring force is presented in the system because of elastic behavior of rubber particles.

Meanwhile, to achieve a softer system with a longer period, one can increase the length of sleeve as well as using a mixture with more rubber particles. It is also suggested to evaluate the size of sleeve pipe on this isolation system performance. As the main conclusion, this proposed system has a good deformation ability and damping characteristics, and could be reported as an efficient method of seismic isolation.

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