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Research Article

INVESTIGATION OF THE EFFECTIVENESS OF VISCOUS DAMPERS CONNECTED TO ADJACENT BUILDINGS ON DYNAMIC BEHAVIOR UNDER SOIL-STRUCTURE INTERACTION EFFECTS

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ABSTRACT

In this study, the dynamic behavior of two adjacent structures with fluid viscous damper (FVD) was investigated under the influence of earthquake and considering soil-structure interaction (SSI). Adjacent structures with FVD's were analysed for three different soil types. The modelling and analysis were made in two-dimensional (2D) space by using ANSYS package program. Viscous boundary conditions were used on the boundaries of 2D soil model. The analyses results were obtained in terms of displacement, acceleration, and shear force. The effect of FVD was investigated using different connection types. The damping coefficient of FVD's was assumed constant in all analyses. When the results of the analysis are examined, it can be seen that FVD's are effective for seismic response. However, it is necessary to consider the soil-structure interaction. Significant different structural results were obtained between fixed support and three different soil types. For example, in the same model, while the top floor displacement may reduce in Soil Type I, the top floor displacement may increase in Soil Type II. At the end of the study, it was seen that there was no need to connect the FVD to all floors. It was found sufficient to connect a fluid viscous damper only to the top floor (1 FVD) or to the top and middle floor (2 FVD). FVD's have no effect on buildings with the similar dynamic character. In the analysis for seismic control of adjacent buildings, the effect of soil-structure interaction should certainly be taken into account.

Keywords: Fluid viscous dampers, adjacent buildings, soil- structure interaction, seismic response, viscous boundary.

1. INTRODUCTION

In many metropolitan cities of the world, population growth is rapidly occurring due to business life and life-quality. Therefore, high and close buildings are being constructed by engineers to respond to the population growth in limited land facilities. In addition, high-rise buildings are frequently seen in projects such as hotels and business centres requiring parking spaces and green spaces in front of the building. Extreme structural vibrations are caused by natural disturbances such as earthquakes and strong winds affect human comfort. Constructed high and close buildings with traditional methods are more likely to be affected by natural disasters including earthquakes and strong winds. Traditional building design is based on the

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principles of adeq uate strength and elastic behavior. In addition, it is quite difficult to respond to large earthquake effects for buildings constructed with traditional methods. The failure of the traditional method approach has been brought about by major earthquakes such as Kocaeli, Imperial Valley, Loma Pietà, Kobe and so on. It is clear that new structural protection systems are needed to protect the lives and occupier-comforts lived in high buildings. Therefore, various structural control systems are being developed by scientists. It has been observed that traditionally constructed structures do not provide sufficient response to earthquakes and strong wind forces. The materials used in building construction have a certain strength and damping capacity. However, during happening large earthquakes, unexpected forces may occur due to the effect of the ground. It is very difficult to absorb the earthquake energy that occurs during large structural earthquakes only by improving the structural material properties. Therefore, researchers have recently begun to adopt the aseismic design approach, also known as the structural control approach. In addition, various structural damping systems have been investigated in order to meet the damping needs of earthquake and strong wind energy. Structural control systems absorb energy from external influences such as earthquakes and strong winds by converting them into heat energy via dampers. Structural control devices can be classified as active, semi-active, passive and hybrid control systems [1]. An external power supply is required for the active and active damping devices to operate. However, there is no need any external power sources to absorb energy for passive damping devices. For this reason, passive damping devices have attracted the attention of researchers. Each of these devices are installed in a structure and successfully absorb the strong wind and earthquake energy.

Applying structural control systems to each building can be costly. Instead, it may be more economical to implement structural control systems by connecting the two buildings if the buildings meet the requirements. By connecting two neighbouring buildings, the idea of damping earthquake and strong wind energy was firstly mentioned by Klein and Healy [2] and then in Kunieda [3]. Klein and Healy [2] proposed a primitive semi-active approach. The purpose of this approach is to couple two buildings with cables that could be released and tightened (when slack is available) to provide specified dissipative control forces. This system, created by the interconnection of neighbouring buildings, is of great interest to Japan and the USA and is also developed and applied to real buildings [4]. For example, in 2001, three buildings at the 45th, 40th and 35th floors of the Triton Square office complex in Tokyo, Japan was interconnected with active damping systems and 35-ton actuators [4].

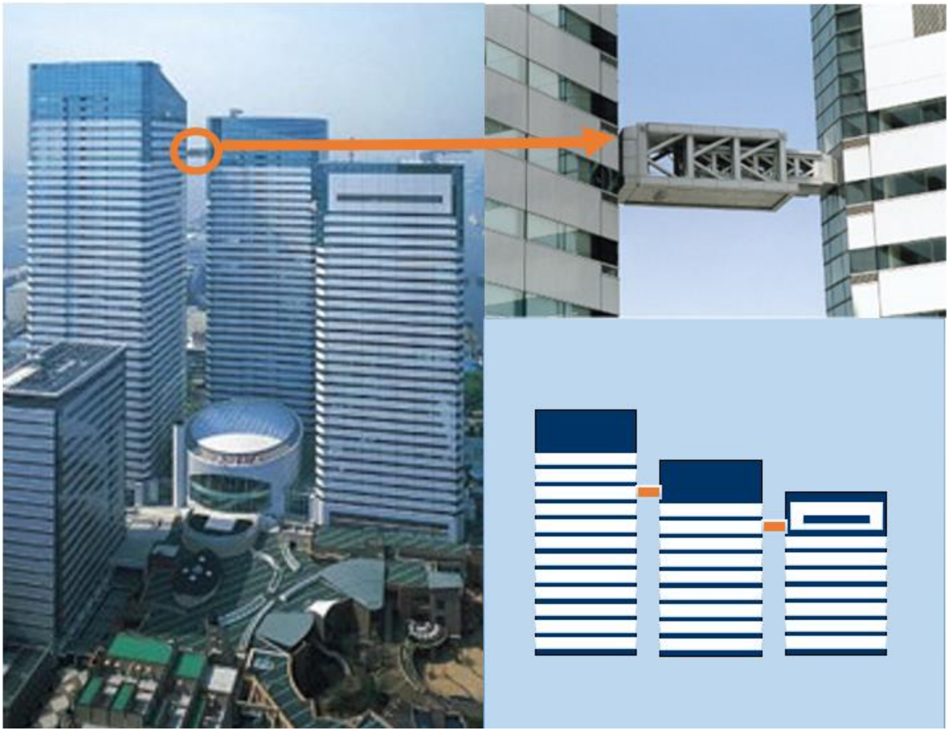

Figure 1. Harumi Island Triton Square Office Tower [4].

Recently, efforts to provide structural control by combining two adjacent structures into each structure rather than applying the structural control system separately have been increasing. Thus, the two buildings can be damped each other. The free space between the two adjacent structures is sufficient to accommodate the structural control devices. No additional space is required for the installation of devices such as viscous dampers. Connecting two buildings to structural control systems prevents collision between two adjacent structures in major seismic events such as the 1985 Mexico City earthquake [5].

Active, semi-active and passive damping devices have advantages and disadvantages over each other. Active damping devices operate on power from an external source. Active damping devices load or suck in energy to the structure according to the vibration movement of the structure. This is an important advantage of active damping devices. These devices need big energies during the earthquake. This energy should not be interrupted during an earthquake. The needs for external energy and for continuous maintenance, and the expensive system are the disadvantages of active damping devices. On the other hand, passive damping devices are systems that do not require external power. One of these devices is fluid viscous damping devices. This device converts energy into heat energy by forcing viscous fluid inside the piston passing through the holes. It is costly and maintenance free. It has 6 degrees of freedom. However, these devices cannot adapt to structural changes. Moreover, semi-active damping devices can be defined as a mixture of active and passive damping devices. Semi-active damping devices interfere with the special fluid inside the piston with the help of electric or magnetic fields and try to provide control of the structure. It doesn't need huge powers. Thanks to electric or magnetic fields, the viscous liquid inside the piston turns into a semi-solid. Similar to the active devices, their disadvantage is that to need external power. Cimellaro and Lopez-Garcia compared structural control devices in terms of issues such as cost, stability, reliability and power requirements [6]. They emphasized that passive damper devices are more advantageous than other structural damping devices. For this reason, Cimellaro and Lopez-Garcia preferred to use passive damping devices and investigated non-linear passive devices connecting two buildings [6]. Patel and Jangid examined structures with single degree of freedom and connected to each other with a viscous damper, considering soil-structure interaction [7]. Depending on the study, Patel and Jangid explained that the inclusion of soil structure interaction is very critical. In another study, Patel examined the structures connected with viscous dampers under four different earthquake data [8]. Patel connected two dynamically identical structures with viscous dampers. The author assumed constant the damping coefficient of viscous dampers and investigated absolute peak displacement, absolute acceleration, shear forces. According to the study, the author emphasized that effective structural control can be achieved by placing viscous dampers in the appropriate place and it is not necessary to connect the viscous dampers on all floor [8]. Patel and Jangid examined the dynamic behavior of two structures connected Maxwell's type viscous dampers using real earthquake data [9]. The authors concluded that viscous dampers connected between two buildings are very effective in reducing the dynamic response of adjacent structures. In addition, the author stressed that it is not necessary to connect a viscous damper to each floor to minimize the cost of dampers. Farghaly connected two buildings with viscous dampers in three-dimensional (3D) space. The author also investigated the effect of different soil types on structural behavior and the damping efficiency of the viscous damper. As a result, the author concluded that soft soil type is more critical than stiff soil type [10]. Xu et al. examined two adjacent buildings connected with viscous dampers under the influence of the 1940 El Centro earthquake in terms of dynamic properties [11]. Authors concluded that the viscous damper was effective for structural control. They have also studied a comprehensive parametric study to find the optimum damping properties of viscous dampers used in adjacent buildings with different stiffness and different heights [11]. Qi and Chang connected and examined adjacent blocks in a large entertainment facility using viscous dampers [12]. Yang et al. conducted an experimental seismic study of adjacent buildings with fluid dampers and examined the effectiveness of fluid viscous dampers [13]. Bhaskararao and Jangid analyzed adjacent structures connected with viscous dampers and studied the optimal damping coefficient for optimum displacement [14], [15]. Kim et al. examined visco-elastic dampers under the influence of real earthquake data. The author connected two buildings with one degree of freedom (SDOF) with visco-elastic dampers [16]. Uz and Hadi used response spectrum analysis and time history analysis in their studies [17]. The authors examined adjacent buildings by connecting them with fluid viscous dampers. Uz and Hadi explored to find best position the viscous dampers how to minimize the cost [17].

Most researchers have examined the dynamic results of two adjacent buildings connected with various viscous dampers under real earthquake data. Based on the study, the interconnected buildings were compared in terms of their dynamic responses to the case before they were interconnected. However, the effect of soil-structure interaction has been neglected in most of the studies. In this study, considering the effect of different soil types on the structure, adjacent structures with linear FVD's was evaluated comprehensive under 1999 Gölcük (Kocaeli) earthquake. The peek displacements, acceleration, base and top shear force values were examined according to different soil types. Also, the effect of the number and position of linear fluid viscous dampers on the dynamic behavior of the structure were examined in detail.

The equations of motion for dynamic model of the coupled buildings are expressed as follow:

$$M\ddot{Y} + (C + C_d)\dot{Y} + (K + K_d)Y = -MI\ddot{y}_g \tag{1}$$

where M is the mass matrices, C is damping matrices and K is stiffness matrices of the adjacent buildings. C_d is the additional damping matrix due to viscous dampers. K_d is the additional stiffness matrix due to viscous dampers. Y is the relative displacement vector with respect to the ground. I is a vector with all its elements to unity and rest equal to 0, and $\ddot{y}_g$ is the ground acceleration at the foundations of the buildings. The additional stiffness matrix (K_d=0) is zero matrices in this study.

2. STRUCTURAL MODELING

In this study, ANSYS R19,2 Academic [10] package program which uses finite element method is used for the modeling.

2.1. Modelling of Buildings and Distribution of Viscous Dampers

The adjacent buildings are called as Building A and Building B. Building A has 6, 12, 18 and 24 storeys. Building B has 6, 9, 12, 15, 18 and 24 storeys. Building A and B interconnected each other at floor level with viscous dampers. The floor heights of all buildings and the distance between two columns are the same. Floor height is 3 m and distance between two columns is 6 m. Selected column and beam dimensions are summarized in Table 1. The distribution of viscous dampers according to the floors is shown in Figures 2-4. The direction of columns A and B is shown in Figure 5.

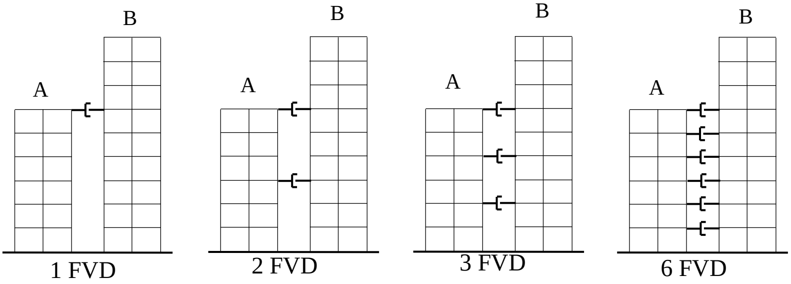

Figure 2. Distribution of FVD's in 6 storey Building A

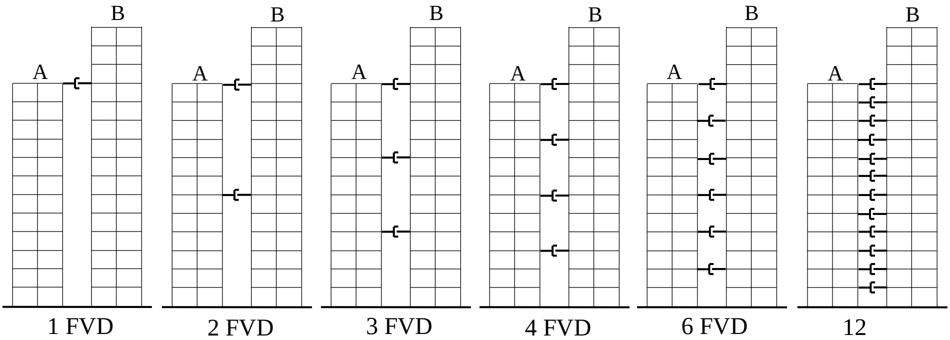

Figure 3. Distribution of FVD's in 12 storey Building A

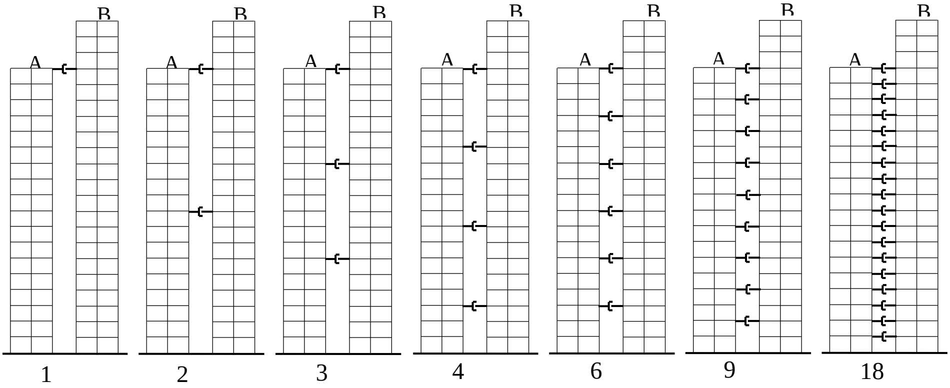

Figure 4. Distribution of FVD's in 18 storey Building A

Table 1. Column and beam dimensions in present study

	Building A				Building B			
Num. of Floors	Beam Height (cm)	Beam Width (cm)	Corner Column Dimension (cm)	Center Column Dimension (cm)	Beam Height (cm)	Beam Width (cm)	Corner Column Dimension (cm)	Center Column Dimension (cm)
6	25	50	25x50	50x25	25	50	25x50	50x25
9	-	-	-	-	30	60	30x60	60x30
12	30	60	35x70	70x35	30	60	35x70	70x35
15	-	-	-	-	35	60	40x80	80x40
18	35	70	45x90	90x45	35	70	45x90	90x45
24	40	70	55x110	110x55	40	70	55x110	110x55

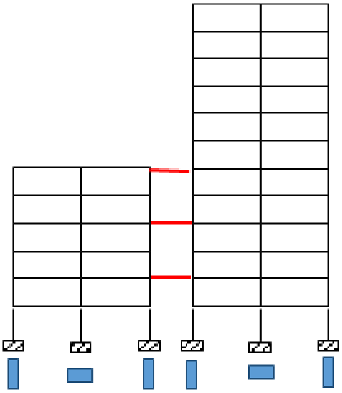

Figure 5. Column directions in present study

2.2. Modeling of Soil Model and Boundary Conditions

Three different soil types are modelled as 2D homogeneous elastic half space. The soil has a width of 210 m and a height of 90 m. Table 2 shows the mechanical properties of soil types.

Transmitting viscous boundary is one of the most commonly used boundary conditions in practice. Because it has the appropriate form for linear and nonlinear finite element analysis. In this study, permeable viscous boundary condition is applied on the soil boundaries. The ANSYS program defines a velocity dependent spring element for all degrees of freedom in order to obtain a viscous limit. The damping coefficient (C) of the spring element depends on the effective area (A) of the finite element to which the spring element is connected, the density (ρ) and the wave velocity (V), which are the ground properties (Equation 2). Modelled soil dimensions are shown in Figure 6.

$$C=A\rho V \qquad (2)$$

Table 2. Values of soil model in this study

Soil Type	Modulus of Elasticity (E)	Poisson Ratio	Mass Density (ρ) kN/m^3	S Wave Velocity (Vs) m/s^2	P Wave Velocity (Vp) m/s^2
I	35	0,4	17	85,75	210,04
II	600	0,32	19	345,86	672,23
III	6000	0,3	21	1048,28	1961,16

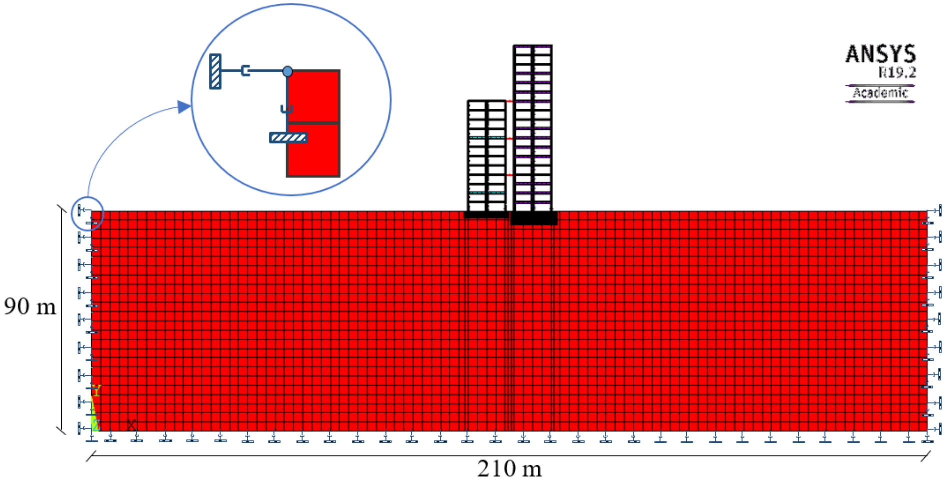

Figure 6. Soil model in present study

2.3. Modelling of Viscous Damper

Fluid viscous damping devices work with the higher flow resistance of viscous fluids. The energy is absorbed by forcing the high viscosity fluid in the device to pass through the designated holes. They are hydraulic devices that absorb the kinetic energy of earthquakes and wind vibrations. Viscous dampers are speed dependent devices. At low speeds, almost no damping occurs. They can be designed to allow free movement. Fluid viscous damping devices are more advantageous than the rest of the devices due to their easy installation, maintenance-free, reliable, long-lasting and no additional power. Fluid viscous dampers consist of oil cylinder, piston rod, lining, center, piston, pin head, protective container of piston rod, pin pedestal for connection and other main parts (Figure 7).

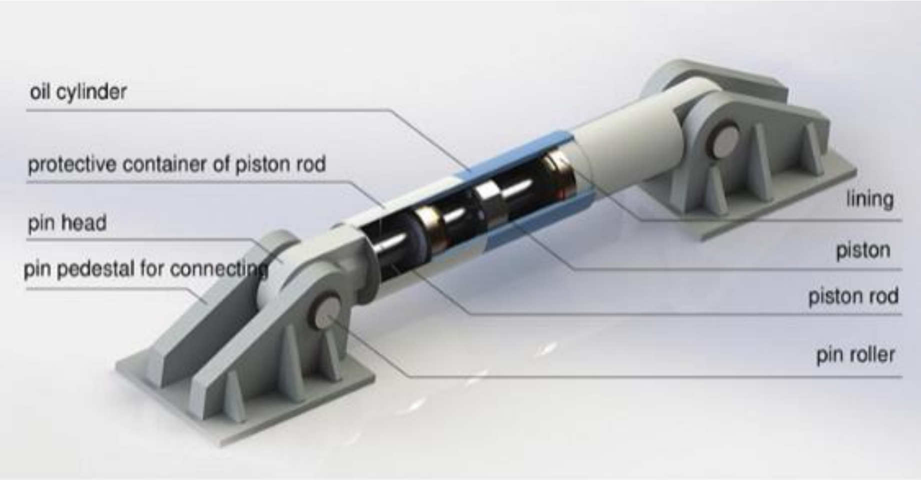

Figure 7. Fluid Viscous Damper [18]

FVD's are known as good energy damping devices commonly used in earthquake protection of buildings. Today, in many construction projects, viscous dampers are used to decrease the structural response with damping the energy provoked by earthquakes or wind [19]. When examined the literature, it is revealed that the connection of fluid viscous dampers and adjacent buildings to each other not only reduces the structural response but also reduces the possibility of collision of the structures.

Linear viscous damper behavior can be expressed by the following equation.

$$\mathrm{F_T} = \mathrm{CV^{cexp}} + \mathrm{KD_K} = \mathrm{F_D} + \mathrm{F_E} \tag{3}$$

where, the total force provided by the damper (F_T), the damping coefficient C, is the spring constant K. V is the speed at the damper and D_K is the amount of displacement of the spring at the damper. c exp is the damping exponent. Tezcan and Uluca [19] and Hou [20] conducted studies concerning the damping exponent. They emphasized that the damping exponent should be between 0.5-2. If the damping base is equal to 1, this means that the device is running linearly. F_T's consists of two parts. The first is the damping force F_D, which is equal to $CV^{c\ exp}$. The second is F_E, which has a restoring force. In the numerical data of this study, since fluid viscous damper will be evaluated linearly, c exp = 1.

Viscous dampers were modelled as COMBIN14 elements in ANSYS [21] program. It was connected between the two buildings at the floor levels of the buildings. The damping coefficient of the viscous dampers connecting the buildings to each other was fixed as $Cd=10^5$ N.s/m in this study.

2.4. Earthquake Acceleration Data

In this study, Gölcük (Kocaeli) earthquake in Turkey in 1999 data was used. Earthquake acceleration records were taken from Yarımca (KOERİ330) recording station of PEER Strong Motion Database data center (Figure 8). The 1999 earthquake in Gölcük (Kocaeli) was a magnitude of 7.8 Magnitude, which caused 17480 deaths and 73342 damaged buildings [22].

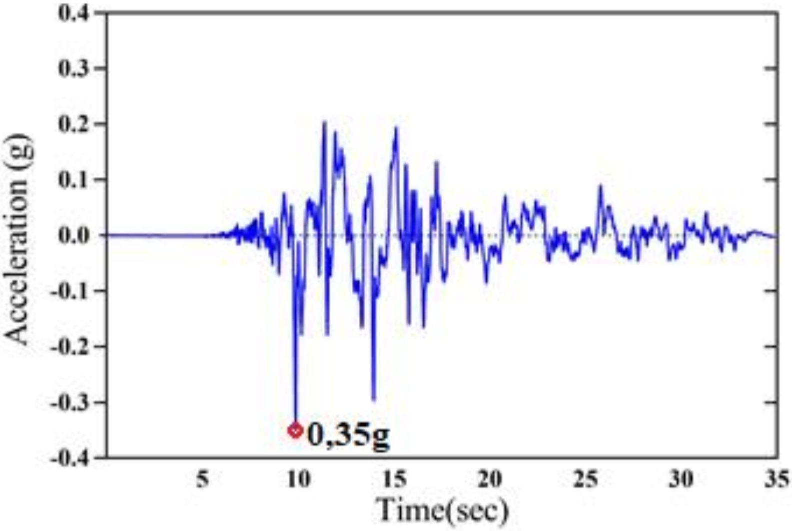

Figure 8. Gölcük (Kocaeli) Earthquake

3. RESULTS AND DISCUSSIONS

Since it was not possible to present all the graphics obtained as a result of the analyses, graphics reflecting the general behavior were presented. Rate graphics are presented. The before and after connection of dynamic values of the buildings are proportioned. Therefore, the values below 1 in the ratio graphs show the improvement in the related value after the buildings are connected to each other. Values above 1 in the ratio graphs indicate the increase in the related value after the buildings are connected to each other.

3.1. Displacement Results

FVD’s have not been very effective in dynamically identical buildings. Because of a fluid viscous damper is a kind of velocity-dependent damper without hardness. Since FVD’s are speed dependent, they generate damping forces by making phase difference with displacements. Since the oscillation of similar dynamic buildings will be the same, FVD’s have no effect. No stiffness, which can be measured in piston movements of FVD’s less than 4 Hz, has been found. If the FVD’s are not properly placed between the two buildings, there is no phase difference and no damping occurs. FVD’s may cause additional stiffness in buildings that oscillate at a frequency greater than 4 Hz. This can sometimes negatively affect building seismic performance. Fluid viscous dampers are very effective in dynamically different structures. For example, when Figure 9 is generally viewed, it can be seen that the decrease in the top floor displacements of buildings is by approximately 35%. Top floor displacement decreases approximately by 60% in Figure 10 and 30% in Figure 11. However, these results vary significantly depending on the soil type. For example, when the graph of 6-storey Building A and 9-storey Building B shown in Figure 9 are examined, the importance of the ground type is clearly visible. In the form of 3 FVD connections (for Building A), the top floor displacement in Soil Type I decreases by 38%, while in Soil Type II it increases by about 22%. Similar situation can be seen in Figure 9, Figure 10 and Figure 11. As the number of FVD’s increased, there is an increase in top floor displacements in some cases. When the two buildings are considered together, it seems that increasing the number of FVD is not effective. When the two buildings are considered together, it can be stated that the most effective connection type is 1 FVD or 2 FVD. This may be due to the 1nd mode shape and the 2nd mode shape of the buildings. So there is no need to connect FVD to each floor level. FVD at appropriate placements can extenuate considerably the seismic responses of the connected buildings and reduce the cost of the dampers. Figure 11, like other graphics, is a good example to explain the importance of soil-structure interaction. At fixed support, the top floor displacement of 18-storey Building A increases approximately 45%, while the top floor displacement decreases by 20% in Soil Type I. There is no clear case for the critical floor type. Critical floor type varies according to the number of floors and connection type. Figures 12-15 show clearly the building oscillation effect of FVD's. FVD's reduce not only the peak displacement, but also the displacements made by the building during the earthquake effect. Therefore, it can be defined that they have an impact on the earlier stabilization of buildings.

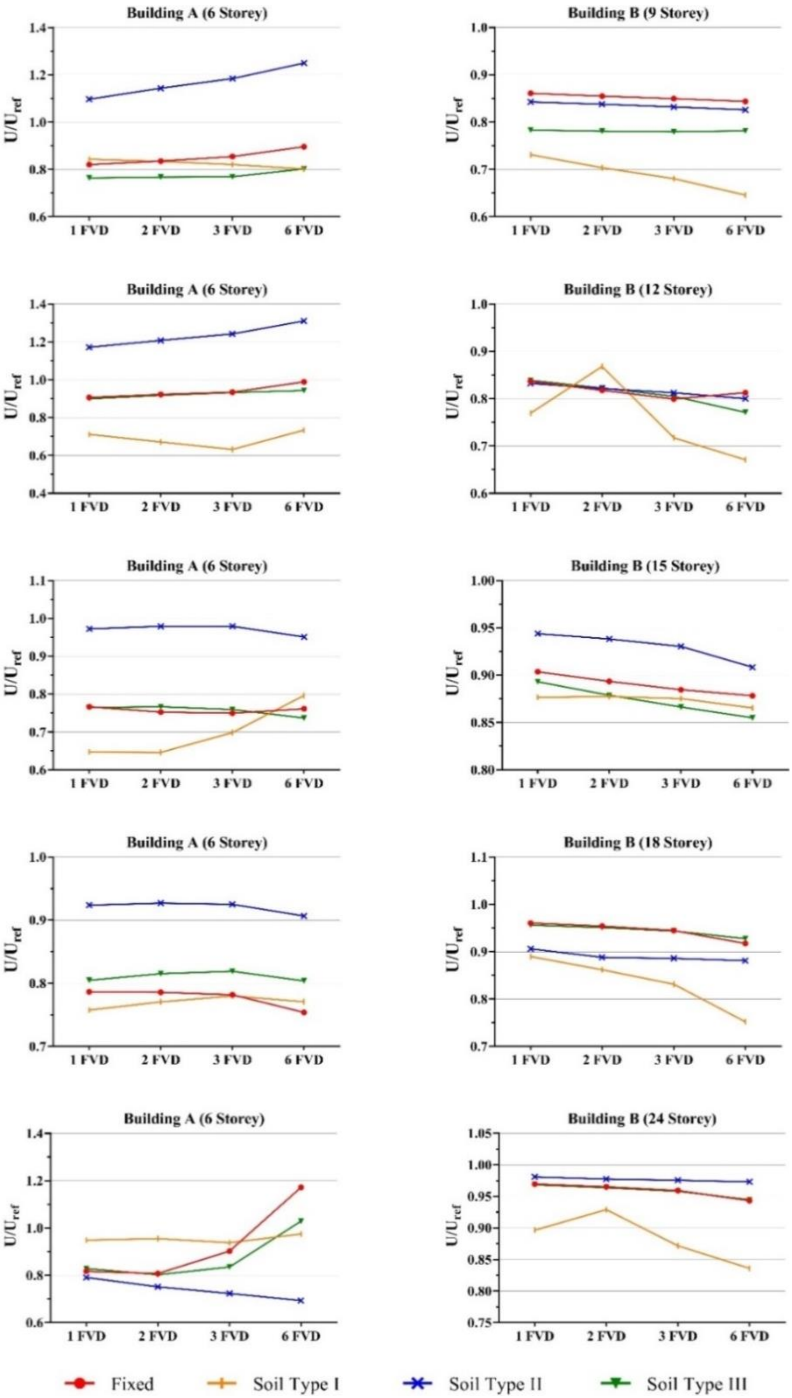

Figure 9. Top floor displacement rate graph of 6-storey Building A and Building B

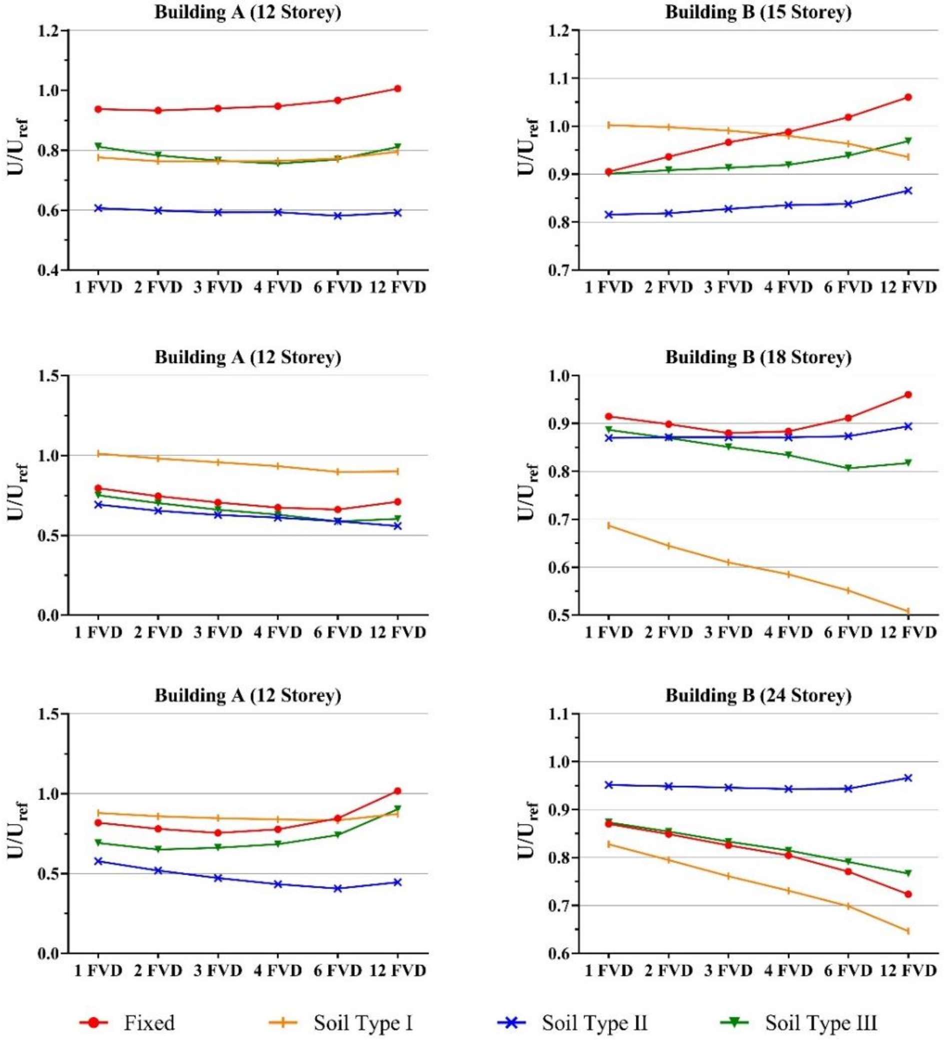

Figure 10. Top floor displacement rate graph of 12-storey Building A and Building B

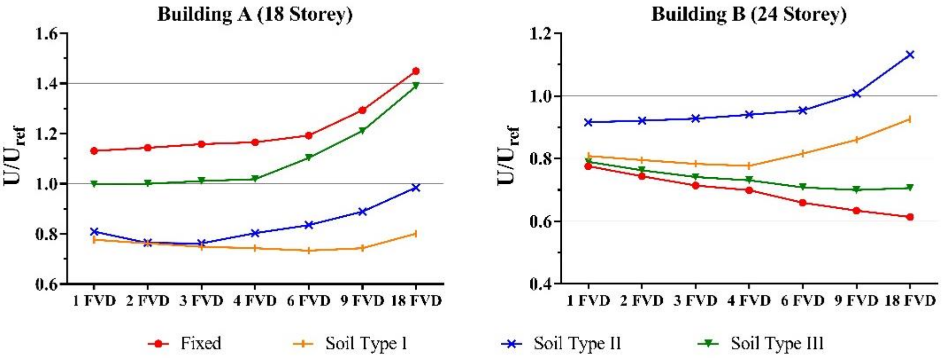

Figure 11. Top floor displacement rate graph of 18-storey Building A and 24-Storey Building B

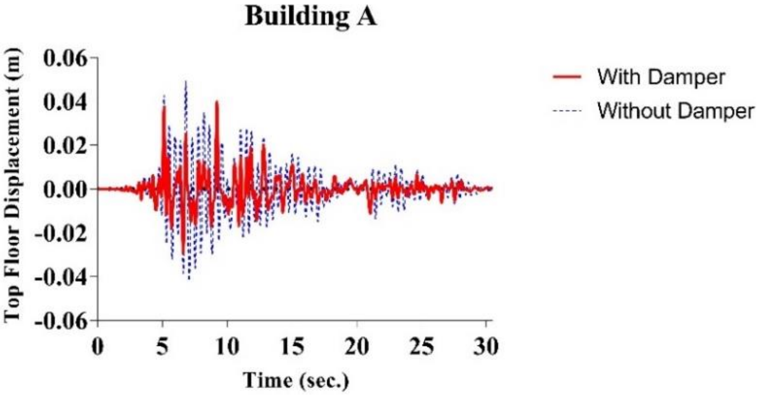

Figure 12. Top Floor Displacement Time History of 6-Storey Building A (Soil Type III)

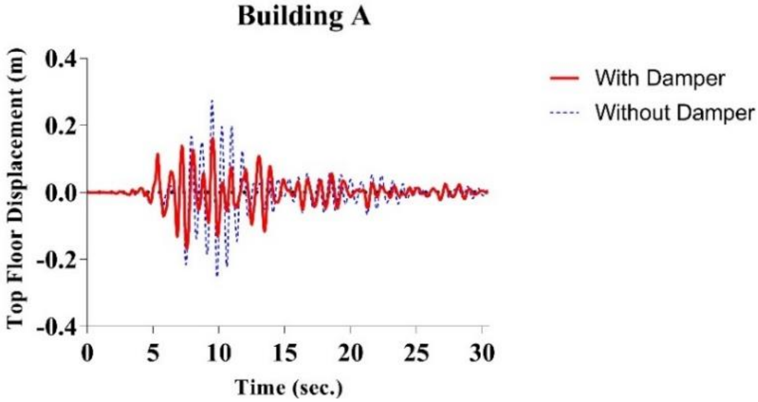

Figure 13. Top Floor Displacement Time History of 12-Storey Building A (Soil Type II)

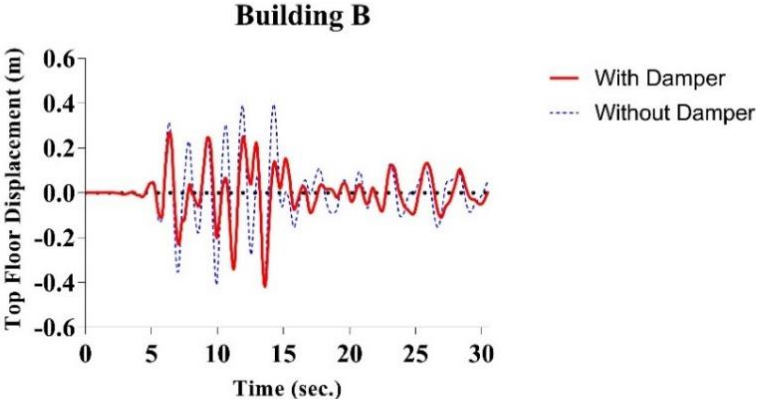

Figure 14. Top Floor Displacement Time History of 18-storey Building B (Soil Type I)

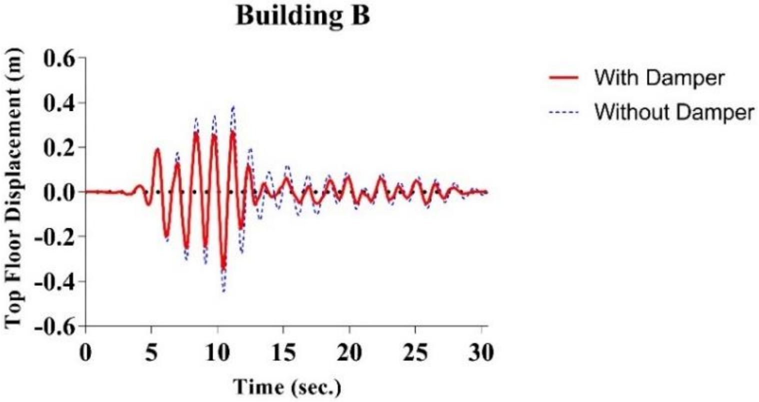

Figure 15. Top Floor Displacement Time History of 18-storey Building A (Fixed)

3.2. Acceleration Results

Figures 16-18 show the top floor acceleration rate graph. When the graphics are examined, connecting the buildings with the FVD’s decreases the acceleration value. Especially Building A has benefited more. The top floor acceleration decrease by more than 50% in Building A. The decline in Building B is found to be by 35%. The top floor acceleration decreased by 35% in Building B. However, it is very important to consider the soil-structure interaction. For example, in Figure 18, in Building B, the top floor acceleration value decreases by approximately 35% on Soil Type III and fixed support, while the top floor acceleration value of the same building increases by 30% in Soil Type I. Similar cases are seen in Figures 16-17. The importance of soil-structure interaction can be clearly realized in the graphics. When Buildings A and B are evaluated together, it can be pointed out that the most effective connection type is only the top floor (1 FVD) or the top floor and middle floor (2 FVD). In general, FVD’s were more effective in Soil Type I when the graphics are examined.

3.3. Shear Force Results

Figure 19 shows the shear forces occurring in the connection of 6-storey Building A and 18-storey Building B with FVD's. When the graph is examined, it is observed that the FVD's in general remarkably reduce the base shear force. The reductions of the base shear force are determined to be nearly 30% and 40% for Building A and Building B, respectively. However, the base shear force in Building A increases by 27% in Soil Type I. the necessity of the soil-structure interaction emerges once again. Figure 20 shows the shear forces that occur when connected 12-storey Building A and 18-storey Building B with FVD's. When the graph is examined, it is seen that the FVD's in general tremendously decrease the base shear force. The base shear forces of Building A and Building B decline by roughly 54% and 42% respectively. However, in fixed support, the base shear force increases by approximately 20% in Building A and 3% in Building B. This important difference shows the importance of soil-structure interaction. Similar cases are given in Figure 21.

The top floor shear forces of Building A, which is shorter than Building B, have generally increased. This is because; FVD's are connected to the top floor of Building A. Although the increases occur in the top floor shear force of Building B, the percentage of change is rather small.

FVD's are distributed to other floors starting from the top floor of Building A. In all analysis models, Building A is equal or shorter than Building B. Therefore, when all the shear force graphs of Building B are examined, discontinuities (up to the number of floors of Building A) appear. These discontinuities are because of the effect of FVD's.

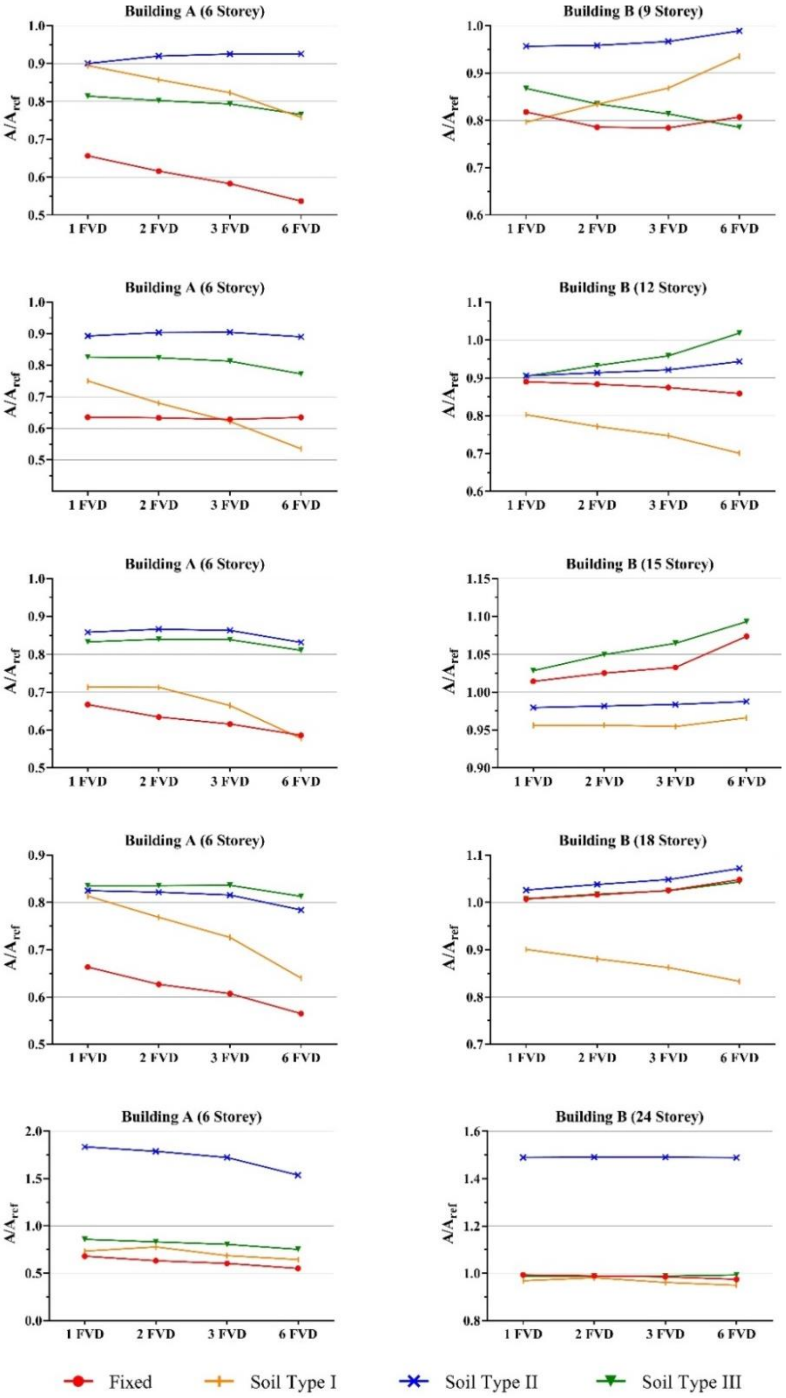

Figure 16. Top floor acceleration rate graph of 6-storey Building A and Building B

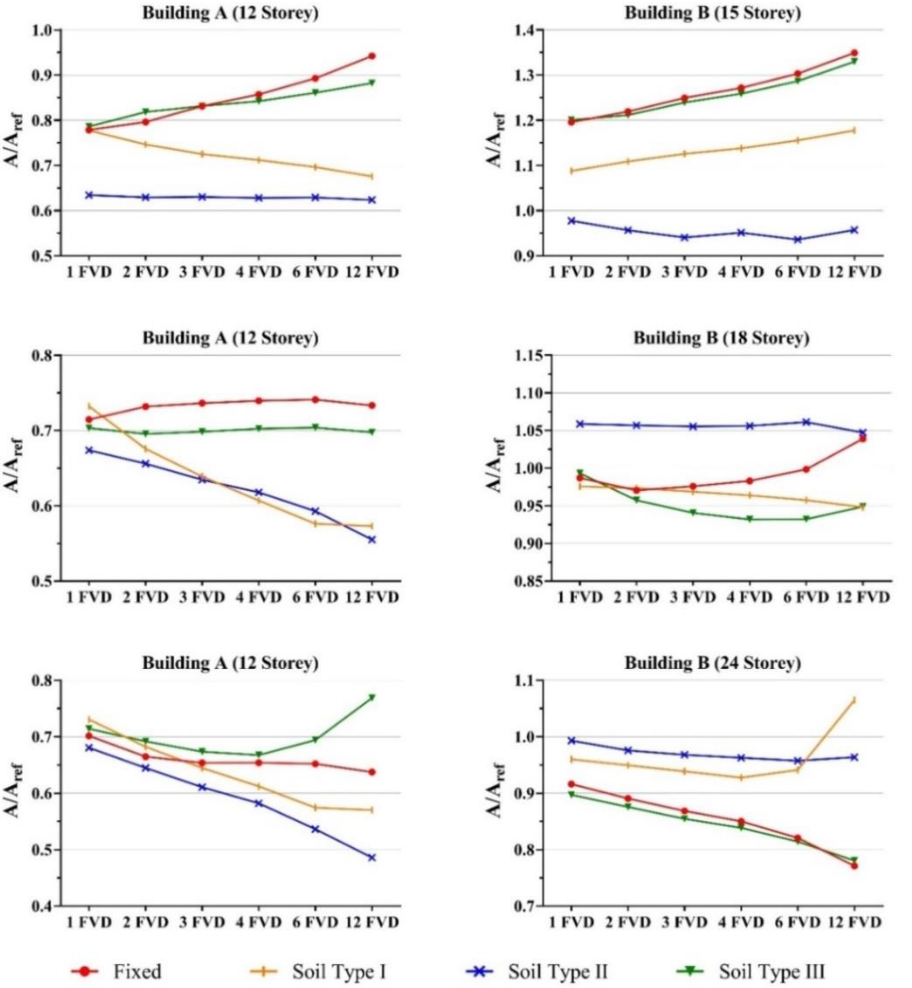

Figure 17. Top floor acceleration rate graph of 12-storey Buildings A and Buildings B

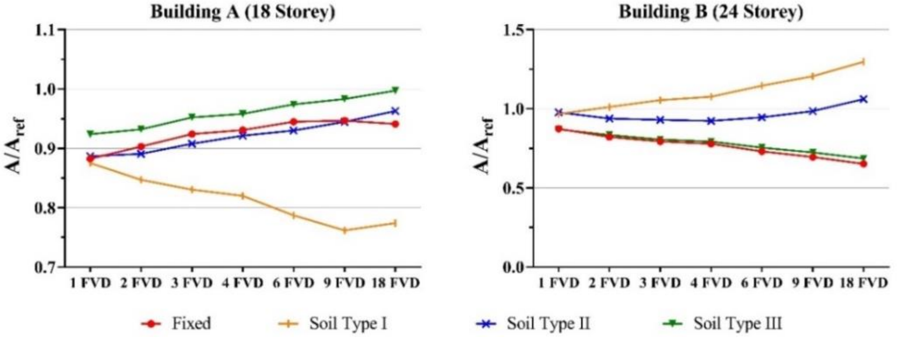

Figure 18. Top floor acceleration rate graph of 18-storey Building A and 24-Storey Building B

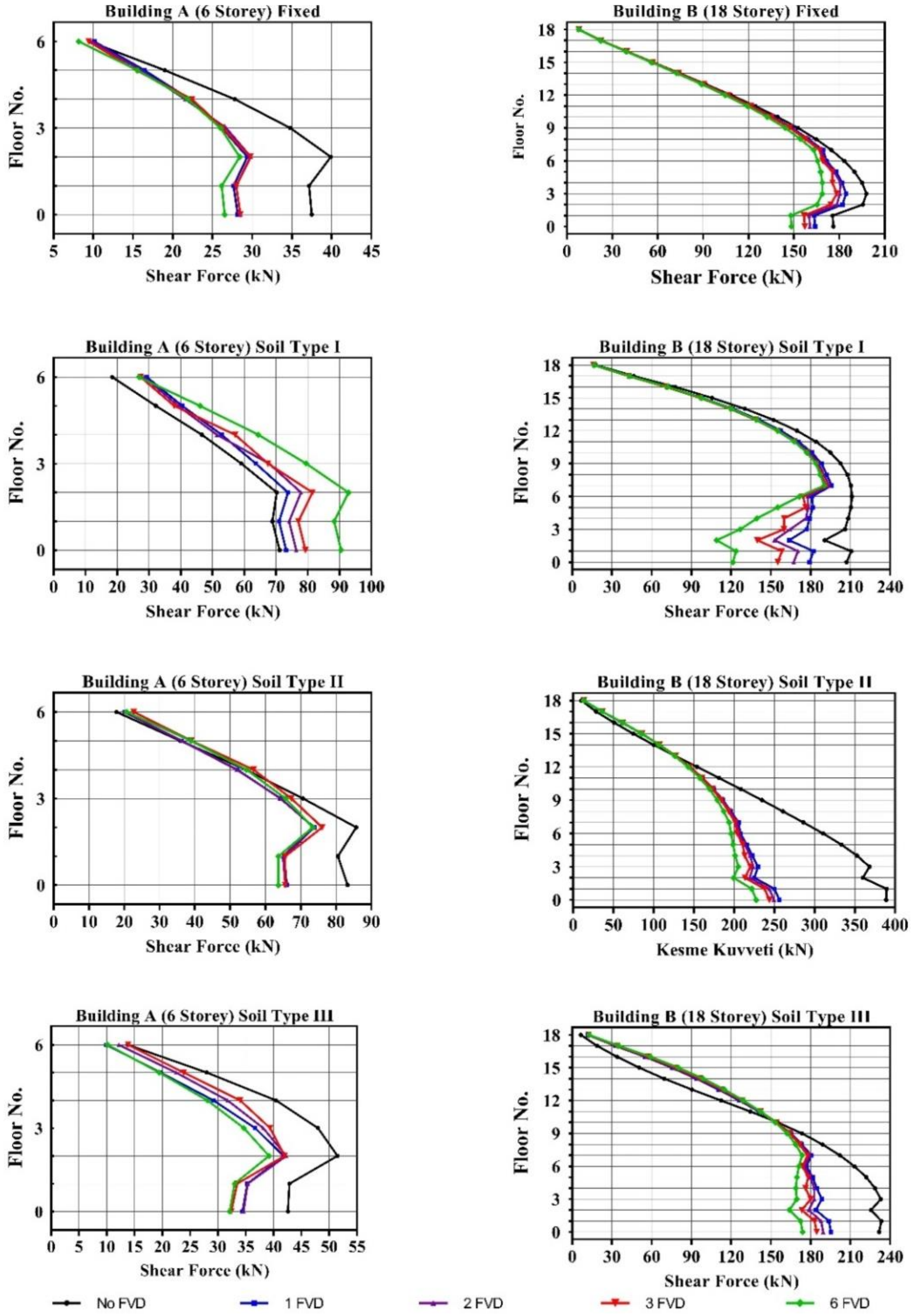

Figure 19. Shear force graph of 6-storey Building A and 18-storey Building B

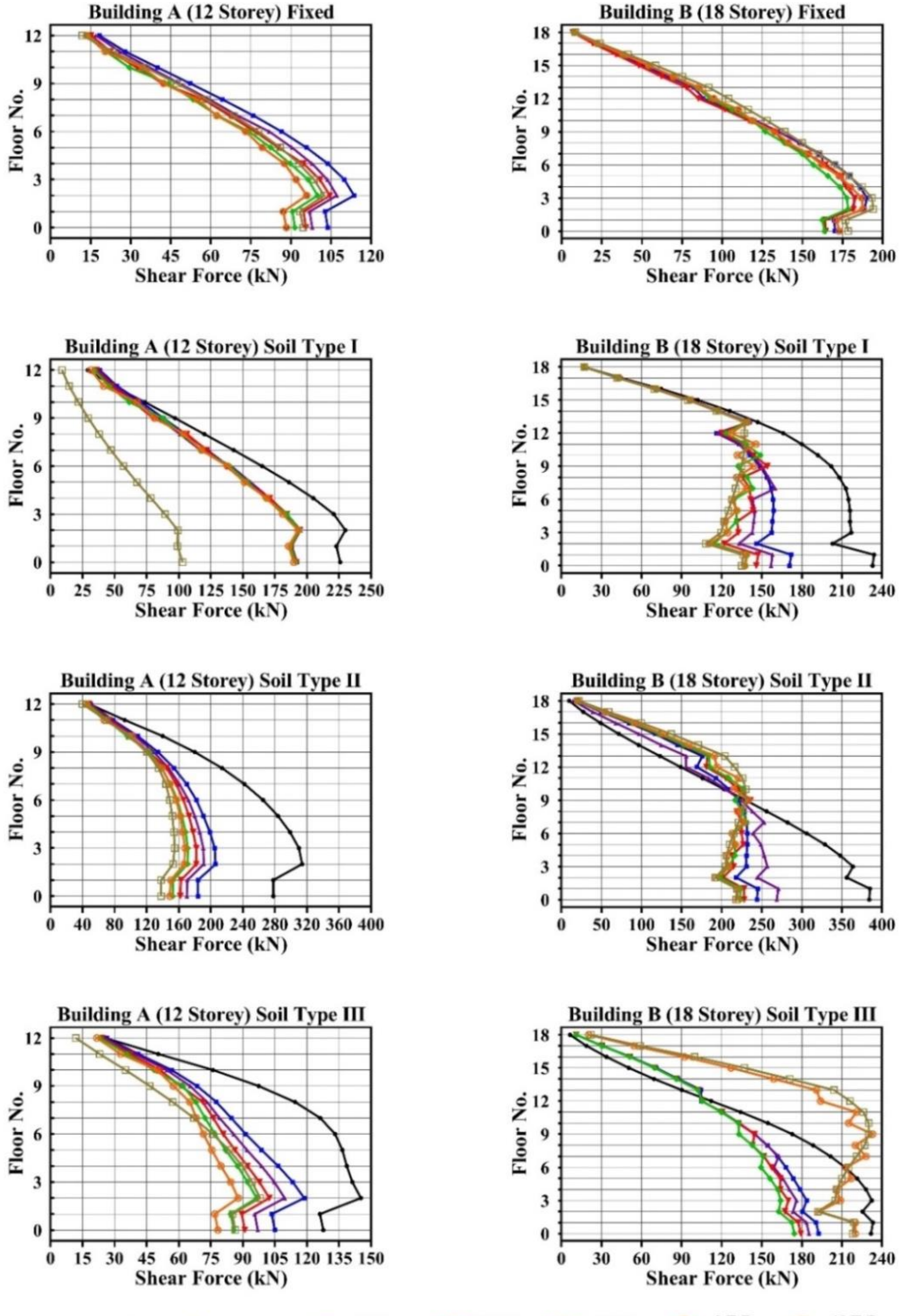

Figure 20. Base shear force graph of 12-storey Building A and 18-storey Building B

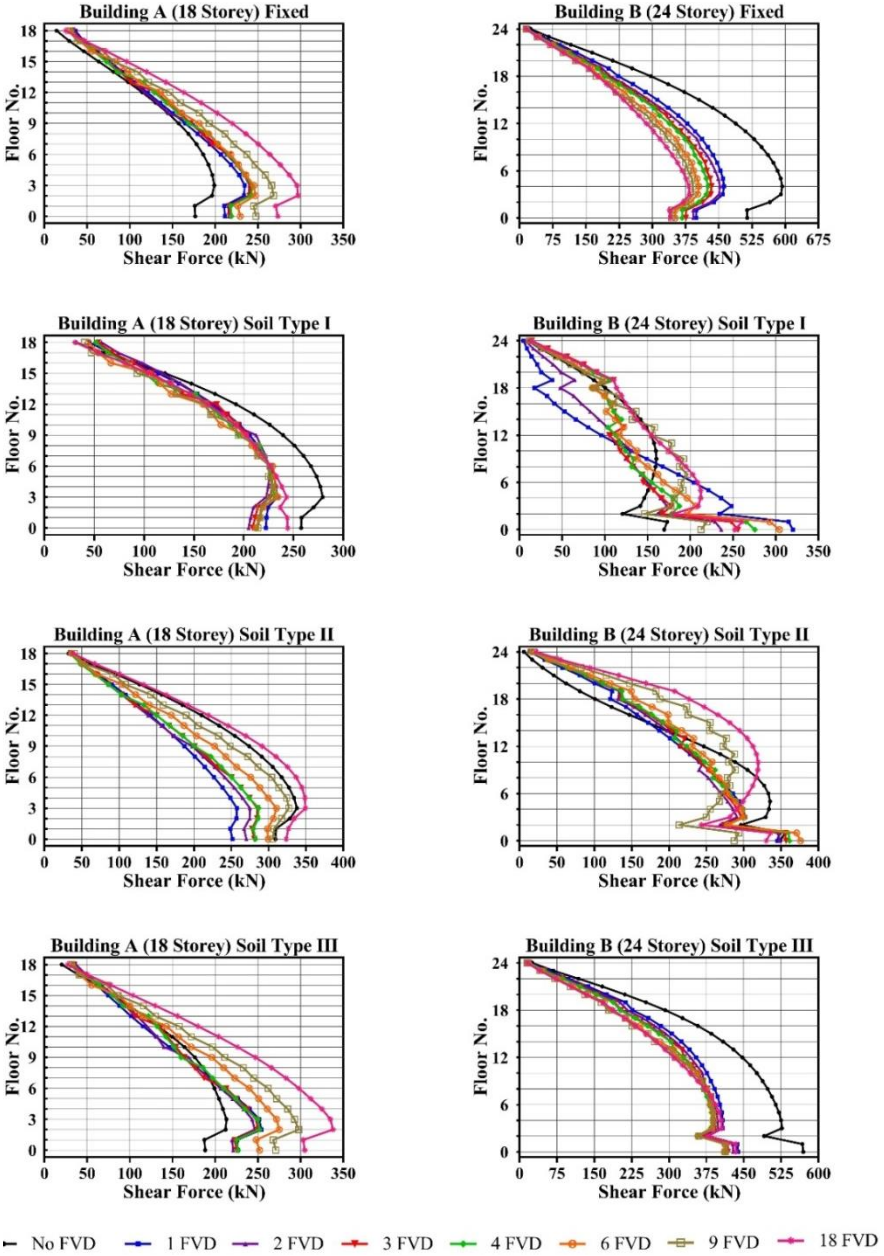

Figure 21. Shear force graph of 18-storey Building A and 24-storey Building B

4. CONCLUSIONS

Building A and B on three different floor types are connected with viscous dampers. Soil types are chosen to represent soft, medium and stiff. The transmitting viscous boundary condition is applied to the boundary model limits. The analyses are carried out by keeping the damping coefficient of the viscous dampers constant (Cd = 10^6 N.s / m) in various numbers and various places. The two buildings with different floor numbers are connected with various combinations. 1999 Gölcük (Kocaeli) earthquake is applied to these buildings and their analyses are carried out in ANSYS R19,2 Academic program. As a result of the analyses, displacement, acceleration and shear force are examined comprehensively.

According to the results obtained from the models determine in this study, it is observed that fluid viscous damping devices provide 40% reduction in displacement, acceleration, base and top floor shear forces of buildings. The fluid viscous dampers are found to be very effective in reducing the seismic responses of the connected buildings. FVD devices can be preferred to increase the seismic performance of the buildings. However, in order to occur this important effect, two buildings with the correct dynamic structure and the right connection type are required. Besides all this, exactly, the analysis should take into account soil-structure interaction effects.

There is an appropriate placement of dampers for minimum earthquake response of the two adjacent connected buildings. The top floor displacement in Soil Type II in the graph (Building B - 18 FVD) increases by about 20%, while it decreases by about 30% in Soil Type III and by about 40% in fixed support. In 1 FVD connection, there are decreases in all floor types and fixed support. This cases appears in the acceleration and shear force graphs a lot. The graphic clearly demonstrated the importance of appropriate placement of FVD's and soil-structure interaction. When the two buildings are considered together, it can be expressed that the most effective connection type is 1 FVD or 2 FVD.

The top floor displacement value in Soil Type I diminishes by approximately 20% (18 FVD), and increases by 40% in Soil Type III and fixed support (18 FVD). This important difference in the same model clearly shows the importance of soil-structure interaction. This case is also seen in the acceleration and shear force graphs. When the values occurring in three different soil types, which correspond to soft, medium and stiff soil types, are compared to fixed support, significant differences occur. These differences are summarized below,

- The top floor displacements occurring in Soil Type I, Soil Type II and Soil Type III are 4, 3 and 1,2 times,
- The top floor acceleration occurring in Soil Type I, Soil Type II and Soil Type III are 4, 3 and 1,2 times,
- The base shear force occurring in Soil Type I, Soil Type II and Soil Type III are 2.6, 3.2 and 1,3 times,
- The top shear force occurring in Soil Type I, Soil Type II and Soil Type III are 2.2, 2.8 and 0,8 times, respectively are different when compared with those of the fixed support.

As a result, the seismic control of the two buildings can be achieved with fluid viscous dampers. It is very important to determine the optimum location and number of fluid viscous dampers. Certainly, in the analysis for seismic control, the effect of soil-structure interaction should be taken into account. FVD has no effect in similar dynamic structures.

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