Earthquakes and Structures, *Vol. 16, No. 6 (2019) 743-755*
DOI: https://doi.org/10.12989/eas.2019.16.6.743

Suspended Columns for Seismic Isolation in Structures (SCSI): A preliminary analytical study

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(Received August 17, 2018, Revised March 17, 2019, Accepted April 10, 2019)

Abstract. In this paper, a new system of seismic isolation for buildings - called suspended columns - is introduced. In this method, the building columns are placed on the hinged cradle seats instead of direct connection to the foundation. In this system, each of the columns is put on a seat hung from its surrounding area by a number of cables, for which cavities are created inside the foundation around the columns. Inside these cavities, the tensile cables are hung. Because of the flexibility of the cables, the suspended seats vibrate during an earthquake and as a result, there is less acceleration in the structure than the foundation. A Matlab code was written to analyze and investigate the response of the system against the earthquake excitations. The findings showed that if this system is used in a building, it results in a significant reduction in the acceleration applied to the structure. A shear key system was used to control the structure for service and lateral weak loads. Moreover, the effect of vertical acceleration on the seismic behavior of the system was also investigated. Effect of the earthquake characteristic period on the system performance was studied and the optimum length of the suspension cables for a variety of the period ranges was suggested. In addition, measures have been taken for long-term functioning of the system and some practical feasibility features were also discussed. Finally, the advantages and limitations of the system were discussed and compared with the other common methods of seismic isolation.

Keywords: seismic isolation; base isolation; suspended columns; passive control; cable hanger

1. Introduction

Seismic isolation is a method for reducing the effect of earthquakes on structures. Up to now, various methods for structural seismic isolation have been invented and their number is still increasing. This is due to the proper functioning of the previously isolated structures under occurred earthquakes. When a structure is directly connected to the ground, movements and accelerations of the ground are directly transmitted to the structure. In this case, the members of the structure must be strong enough to withstand the earthquake-induced forces. By isolating the structure from the ground and placing an intermediary system between them, the amount of acceleration is limited and the damage to the structure is greatly reduced. Seismic isolations have been used in a variety of structures, such as buildings, bridges, industrial equipment, and nuclear power plants. This method may be used to reduce the effect of excitations other than earthquakes, such as the vibration effects caused by vehicles on bridges. However, the main research in this area is the studying of isolators under the earthquake excitations. So far, different seismic isolation techniques have been developed, each of them have limitations. Some of them have the high cost of construction, while others have practical restrictions. Some of them have maintenance problems during the lifetime of the structure. Therefore, some of these methods are more useful and practical than others and some have remained in the theoretical phase. Among the most widely used and old methods of isolation is the lead rubber bearing (LRB) system which was invented by Robinson and Tucker, (1977), Robinson (1982), and complementary research work has been done on the LRB by various researchers (Nagarajaiah and Ferrell 1999, Ryan *et al*. 2005). As the LRB has shown very good performance in different earthquakes, therefore, it has become one of the most commonly used seismic isolation methods. That is why many studies have been done in this regard and the results have been published (Naeim and Kelly 1999, Skinner 1993). Moreover, methods with similar function, such as the Resilient Friction Base Isolator (R-FBI), have been invented and introduced (Mostaghel and Khodaverdian 1987), Another method of seismic isolation is friction based sliding isolators. The different types of this method were introduced as single-layer, double-layer, and triple-layer types (Fenz and Constantinou 2006, 2008a, b, c, Wei *et al*. 2017). The simplest type of the system is the single-layer one, which was investigated by some researchers such as Zayas *et al*. (1990). Later, it was improved and called Variable Frequency Pendulum Isolation (VFPI) system by Pranesh and Sinha (2000, 2002), by changing the radius of

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ISSN: 2092-7614 (Print), 2092-7622 (Online)

curvature of the sliding surface. The system has also been studied experimentally and its laboratory behavior compared to the theoretical calculations (Xilin 2017). Wei Xiong *et al*. (2018) proposed a pyramidal sliding isolation system in which the sloped surface with a fixed slope was used. Lu and Yang (1997), investigated fictitious sliding support method, and Chu *et al*. (2013), studied on the characteristics of dry friction plate-reset spring seismic isolation system. Mokha *et al*. (1990), researched on Teflon Bearings in the base isolation. Virginio *et al*. (2017, 2016), investigated theoretically and experimentally on the curved surface sliders emphasizing on the re-centering capability. Another seismic isolation system is a ball-based system that has been proposed by some researchers. Zhou *et al*. (1998), studied on the metal balls in concave supports with restoring capability. Guerreiro *et al*. (2007), carried out seismic tests and numerical modeling of a rolling-ball isolation system. Barghian and Beirami Shahabi (2007), proposed a so-called pendulum base isolation that had a restorative function, for the first time and later it was tested experimentally in a lab by Lu and Hsub (2013a, b). In this system, the reciprocal mushroom shaped pedestals are connected to the bottom end of the ground floor columns as a pin joint. In this way the structure moves freely to the sides, hence, isolation is done. The system known as Roll-N-Cage (RNC) consisting of an orb together with an upper and a lower seat - responsible for the force distribution on the orb surface - was studied by Mohammed Ismail *et al*. (2012, 2016). In addition to the metal ball, a number of researchers have studied the roller isolators. Jangid and Londhe (1998), Jangid (2000), proposed elliptical rolling rods for the base isolation. Chung *et al*. (2009) used metal rods, which had an eccentricity to provide restoring force. In order to provide isolation in two perpendicular directions, the orthogonal rod system was proposed and examined theoretically and experimentally, (Foti *et al*. 2011, Chen and Wang 2016). Wei *et al*. (2017, 2018a) investigated the rolling isolation systems with concave and convex friction distribution. They found that the concavely distributed friction force could change the structural natural period. In the other work, (Wei *et al*. 2018b) studied on the scaling of pure friction isolation system for shaking table model tests which can be used to perform laboratory tests of low damping systems similar to the system proposed in his paper. Chen and Shiang (2016) modified the sloped rolling-type isolation system with the addition of electric magnets and invented a semi-active isolation system, in which the movement of the rolls was controlled by the passage of the electric current and could provide the desired movement stiffness. Aruna *et al*. (2018) developed an orthogonal rod isolation technique with elliptical bars, in which the restoring forces were created in the system. Nakamura *et al*. (2011) investigated the effect of using the isolator on the structure topology; in their work, the structure was isolated as the core and body. One of the problems of the isolators is the remaining of permanent deformation in isolators after the earthquake. To overcome this problem, a special invention was made by Spizzuoco *et al*. (2016), by using tensile cables. Hosseini and Farsangi (2012) introduced a new isolation system for the vibration control of high-rise buildings called Telescopic columns. In their system, a main column is considered at the center of mass of the structure on the ground floor and this column is pin connected to the bottom of the structure. The rest of the ground floor columns are telescopic with an axial deformation capability. The telescopic columns provide isolation by cradling motion. Karayel *et al*. (2017), proposed spring tube braces for seismic isolation of buildings. In their proposal, the columns of the ground floor were erected as two ends pinned; spring brakes were constructed on the ground floor and all together, by a soft story mechanism, they created seismic isolation. High-construction cost and technology are the main disadvantages of the current isolation systems that restrict the use of these techniques. Losanno *et al*. (2019) proposed a polyester fiber-reinforced rubber, which had a low cost of construction and implementation. They used polyester fiber rather than carbon fiber in the proposed system, which had a lower cost acquiring comparable seismic performance with carbon fiber. Calabrese *et al*. (2019) conducted laboratory experiments on Recycled Rubber - Fiber Reinforced Bearings (RR-FRBs) and studied the seismic behavior of the isolator under earthquake acceleration and obtained the necessary parameters for analytical modeling.

Almost all of the proposed methods for seismic isolation have disadvantages along with their advantages. Therefore, it is necessary to continue the research in this field to eliminate the disadvantages and improve the performance of isolators. For example, LRB isolators have high cost and restriction on lateral displacement. In the friction isolators, there is a possibility that the sliding surface would be welded during the time and stress concentration problem is raised in the rolling isolators.

In this research a new method called suspended columns for seismic isolation in structures (SCSI) is presented. This method has almost all of the appropriate isolator capabilities and in this system; most of the disadvantages of common isolators have been resolved to a large extent. The current isolators can be replaced by the proposed method if supplementary studies are accomplished and its executive specifications are determined. In this method, the structure is attached to the foundation as a pendulum so that the transmission of severe ground acceleration to the structure is prevented.

2. Proposed method: Suspended columns for Seismic Isolation in structures (SCSI)

This method acts like a clock pendulum in which the columns of the structure are mounted on the hanged seats (supports). The seat is hung from the foundation by cables. In this way, the connection between the structure and the foundation will be through these cables. Fig. 1 shows the schematic shape of this method. In this method, cavities - such as the elevator pit - are created in the position of columns during the construction of the foundation and a stiffened steel plate is installed on the upper perimeter of the cavities (upper support). The hanger cables are attached to this support from one end and hung into the hole and

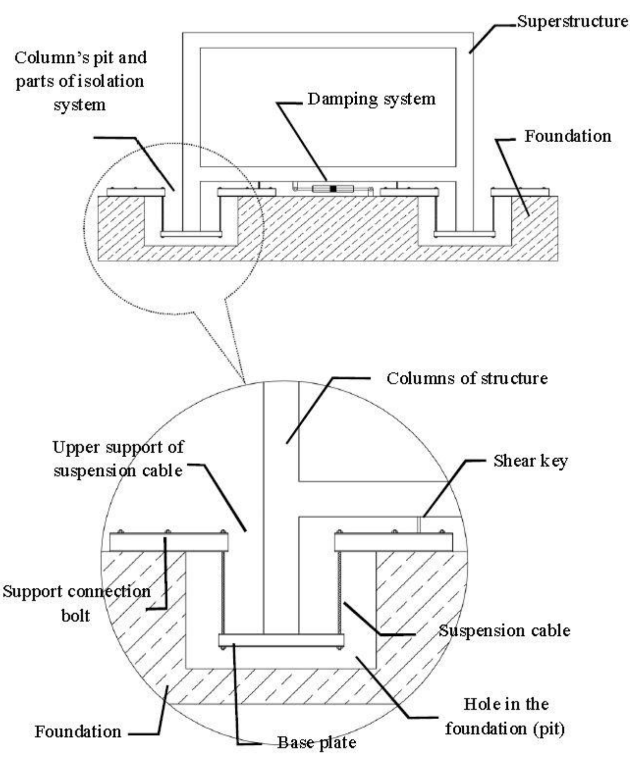


Fig. 1 Schematic drawing of the suspended columns for the seismic isolation system (SCSI)

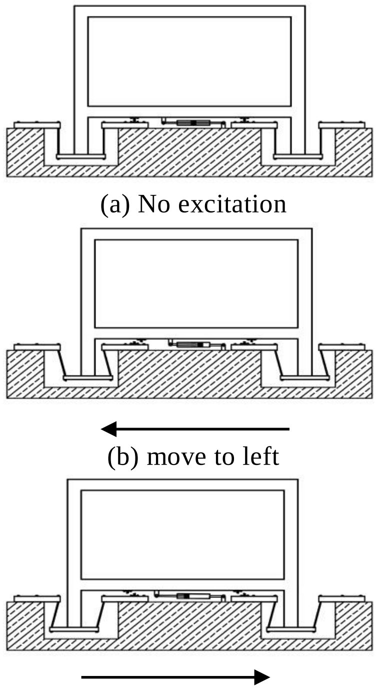


Fig. 2 Different phases of movement of the structure equipped with the proposed isolation system during ground excitation and damper functioning

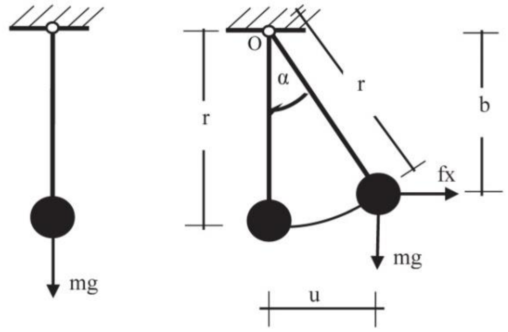
hold a stiffened steel base plate (seat- beneath support) in the bottom of the column, from the other end. In other words, the cables act as an interface between the foundation and structure. The length, width, and depth of the cavities are variable so that they depend on the dimensions of the columns and hanger cable. Fig. 2 depicts the different movement phases of the structure equipped with the proposed isolation system during ground excitation. Figs. 2(a)-2(c), respectively show the motionless state and moving to the left and right state of the structure caused by ground excitation. It is seen from this figure that during the earthquake, the foundation of the structure moves to left and right, while the structure itself remains almost in its original position. This mechanism creates the isolation of the structure and significantly reduces the acceleration transmitted to the structure. For better performance of this system, there is a need for damping in the structure, which can be achieved by installing additional dampers, such as a viscous damper, as shown in Figs. 1-2.

The dimensions of each cavity should be sufficiently larger than the corresponding cross-sectional dimensions of the column, which will be hung inside the cavity. The reason is that the column can freely move to the sides during an earthquake while it does not hit the foundation body. The more the height of the cavity, the more will be possible to increase the length of the suspension cables. The number and diameter of the cables should be determined by the weight of the structure and the amount of the force of each column by considering a suitable safety factor. All cables are attached to a base plate (seat) and withstand the tensile force which is equal (in amount) to the compressive force of a column on the seat. The ends of the cables are almost pinned and the bending moment in cables is ignored.

After connecting the structure to the foundation by suspension cable, the force of the column is transmitted through the cables to the upper part of the foundation. This mechanism creates a pendulum seismic isolation system. Thus, the foundation moves during an earthquake, however, since the columns are hung by means of the cables, therefore, the less amount of the ground excitation is transmitted to the structure and the exerted acceleration to the structure will be reduced. To a certain extent, the longer the cable length, the softer structure will be; as a result, less movement will be transmitted to the structure. The appropriate length of cables should be obtained from the analysis. This system oscillates and then returns back to its initial position similar to a pendulum that is one of the advantages of the proposed system. By this way, one of the main problems of previous seismic isolation methods - in which the permanent displacements remained in the structure after the earthquake - is resolved.

3. Modeling of the suspended columns

To obtain the equations of motion of the proposed system, it is assumed as a pendulum system. The simplified model of this system is shown in Fig. 3. As it is seen from the figure, in the model the total weight of the structure is concentrated at the end of the cable hanging from an articulated hinge and it can move to the sides like a pendulum. In the modeling of the system, the following assumptions were made:



(a) Before exiting (b) After exiting

Fig. 3 The simplified model of the suspended columns for seismic isolation, *mg*=total weight of structure

a) The total weight of the structure was concentrated at the end of the columns and this weight was applied at the ends of the cables.
b) The structure modeled as a single degree of freedom (SDOF) and the frame of the structure were taken as rigid.
c) The diameter and number of cables have been appropriately selected based on column compression force and the cables can withstand against these forces.
d) The pit dimensions inside the foundation must be sufficiently larger than the dimensions of the column in order to provide free movement of the column to sides without touching the wall of the pit.

According to the assumptions made above, the entire system can be modeled as a pendulum. Figs. 3(a)-3(b) show the simplified schematic of this system before and after the ground excitation respectively. In the modeling, it was assumed that the foundation was fixed and the structure itself moved to a side (u).

In order to obtain the lateral stiffness of the system in Fig. 3(b), the moment of all system forces was taken about the support point (o), so the following equation can be written

$$\circlearrowright \sum M_o = 0 \quad \Rightarrow mg * u - f_x * b = 0 \tag{1}$$

Where mg is the total weight of the structure, u is the horizontal displacement of mass and b is the vertical distance between the support and the mass of the structure. From the trigonometry relations, the following sentence can be written

$$\sin^2\alpha+\cos^2\alpha=1 \Rightarrow \cos\alpha=\sqrt{1-\sin^2\alpha} \tag{2}$$

Moreover, from Fig. 3 one can write

$$\cos\alpha = \frac{b}{r} \quad \Rightarrow \quad b = r * \cos\alpha \tag{3}$$

$$\sin\alpha = \frac{u}{r} \Rightarrow b = r\sqrt{1-\frac{u^2}{r^2}} \quad \Rightarrow b = \sqrt{r^2-u^2} \tag{4}$$

Where r is the length of the cable. By inserting the Eq. (4) in (1), the Eq. (5) is obtained

$$mg * u - f_x * \sqrt{r^2-u^2} = 0 \quad \Rightarrow f_x = \frac{mg*u}{\sqrt{r^2-u^2}} \tag{5}$$

The value of f_x is the force which returns the structure to its original location after the earthquake movement. The Eq. (5) shows that this system is similar to a mass-spring system, in which during an earthquake, an opposing force is created and causes the structure to return to its original position. This feature is one of the important advantages of the method, and it is one of the major issues in the seismic isolation systems. If the force f_x obtained from Eq. (5), is divided into the displacement of the structure (u), the stiffness of the spring is obtained

$$K=\frac{f_x}{u} \Rightarrow K=\frac{mg}{\sqrt{r^2-u^2}} \tag{6}$$

Where K shows the stiffness of the equivalent spring in the pendulum system. It is seen that the stiffness of the spring is a function of the length of the cable. Therefore, the stiffness of the system can be changed by changing the length of the cable. As the natural period of the structure is proportional to the stiffness of the structure, therefore, the natural period of structure can easily be changed and the desired value can be achieved by properly selecting the length of the suspension cable. This is another advantage of this system that the designer can select the desired value for the period of the structure. The stiffness of the equal spring is a nonlinear function of the ground displacement, so the stiffness of the system has a nonlinear behavior. The system can be simulated as a mass-spring system and from the dynamics of the structure, the equation of motion of a mass-spring-damper system under earthquake acceleration can be written as follows

$$m\ddot{u}+c\dot{u}+Ku=-m\ddot{u}_g \tag{7a}$$

Where m, $\ddot{u}$, c, $\dot{u}$, K, u and $\ddot{u}_g$ are the mass of the structure, the acceleration of mass, the damping coefficient, the velocity of the mass, the stiffness of system, the displacement of mass and the ground acceleration, respectively. By dividing the two sides of the Eq. (7a) into the mass of the structure, Eq. (7b) can be obtained

$$\ddot{u}+\frac{c}{m}\dot{u}+\frac{K}{m}u=-\ddot{u}_g \tag{7b}$$

Moreover, by putting the Eq. (6) into the Eq. (7b) the following equation is obtained

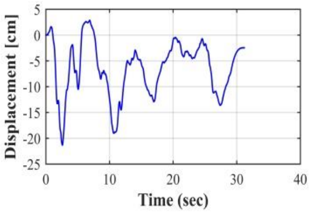
$$\ddot{u}+\frac{c}{m}\dot{u}+\frac{g}{\sqrt{r^2-u^2}}u=-\ddot{u}_g \tag{7c}$$

Eq. (7c) is the equation of motion of a mass-spring-damper system equivalent to the suspended column seismic isolation system.

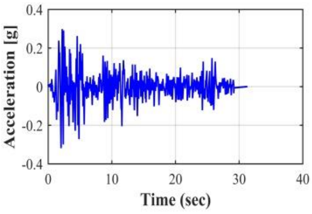
In order to obtain the value of u in Eq. (7c), a Matlab code was written and the response of the system was

Table 1 Selected acceleration characteristics

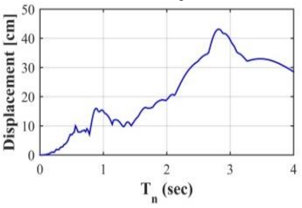
Record	*Ms*	*d* (km)	*PGA* (g)	*PGD* (cm)
El Centro, USA 1940, (Peknold), N-S.	6.95	6.1	0.32	21.4
Chi-Chi, Taiwan, 1999, TCU045, E.	7.62	26.0	0.36	22.9
Kobe, Japan, 1995, Kakogawa, 90.	6.9	22.5	0.345	9.7



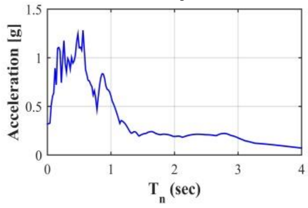
(a) ground displacement time history



(b) ground acceleration time history

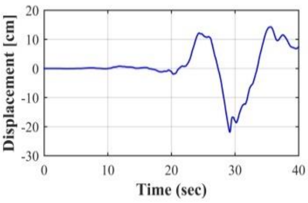


(c) displacement response spectra

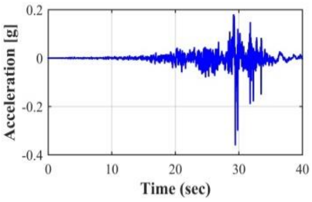


(d) pseudo-acceleration response spectra

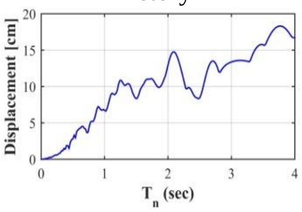
Fig. 4 The El Cenetro earthquake specifications for damping ratio of 2%



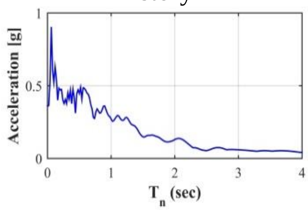
(a) ground displacement time history



(b) ground acceleration time history

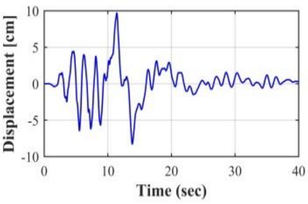


(c) displacement response spectra

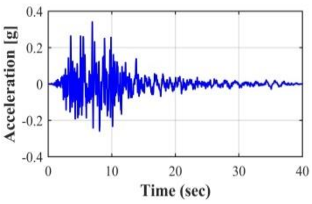


(d) pseudo-acceleration response spectra

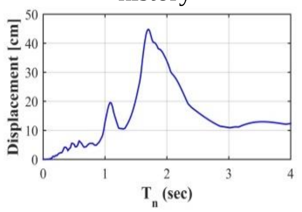
Fig. 5 The Chi-Chi earthquake specifications for damping ratio of 2%



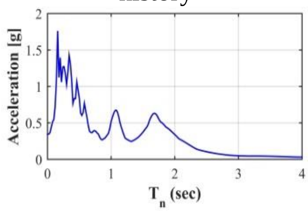
(a) ground displacement time history



(b) ground acceleration time history



(c) displacement response spectra



(d) pseudo-acceleration response spectra

Fig. 6 The Kobe earthquake specifications for damping ratio of 2%

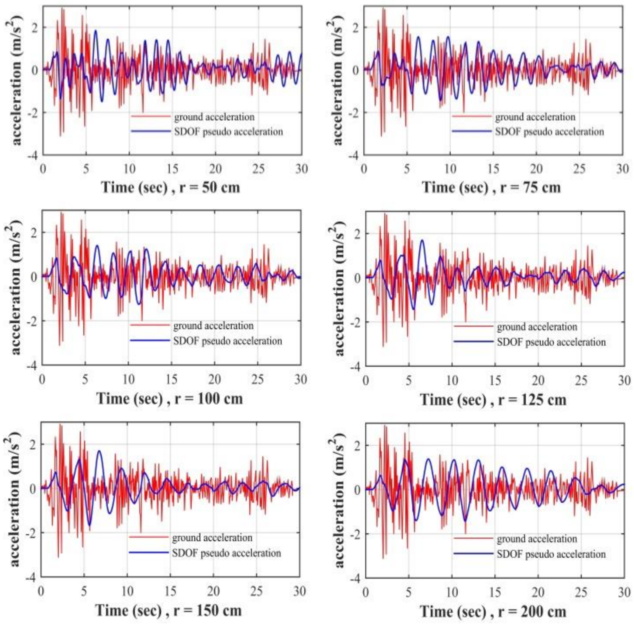


Fig. 7 Ground acceleration and pseudo-acceleration response time-history graphs in the isolated structure with different cable lengths under the El Centro earthquake with a damping ratio of 5%

obtained under the earthquake acceleration. As it is clear from the Eq. (7c), the response of the structure is a function of r. It is possible to control the response of the structure by changing the value of r. Using the written Matlab code, the Eq. (7c) was solved for different r values for the data of three earthquakes. The characteristics of the selected earthquakes are reported in Table 1.

Figs. 4-6 show the ground displacement time history, ground acceleration time history, relative displacement response spectra, and pseudo-acceleration response spectra with a damping ratio of 2% for these earthquakes, respectively. Figs. 7-9 show the time-history plots of the ground acceleration and ground pseudo- acceleration in a single degree of freedom structure, isolated by means of the suspended columns system with the hanger cable lengths of 50, 75, 100, 125, 150, and 200 cm for the three earthquakes and a damping ratio of 5%, respectively.

Also in Figs. 10-12, the relative displacement spectra, pseudo-velocity and pseudo-acceleration spectra of the three earthquakes are plotted for the damping ratios of 2, 5, 10, and 20 percent, respectively.

4. Results and discussion

A Matlab code was written and used to analyze the structure under different earthquake accelerations and the results were plotted. The time-history graph of the ground acceleration and pseudo-acceleration response of the single degree of freedom structure, (SDOF)- isolated by means of the suspended columns system - were plotted with the different hung cable lengths and a damping ratio of 5%. In Figs. 7 to 9, the results of the structural dynamic analysis of the isolated SDOF structure under the acceleration of the

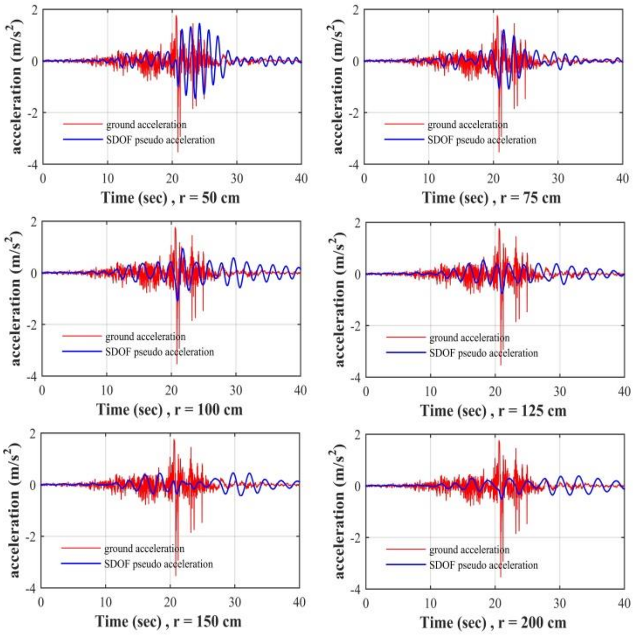


Fig. 8 Ground acceleration and pseudo-acceleration response time-history graphs in the isolated structure with different cable lengths under the Chi-Chi earthquake with a damping ratio of 5%

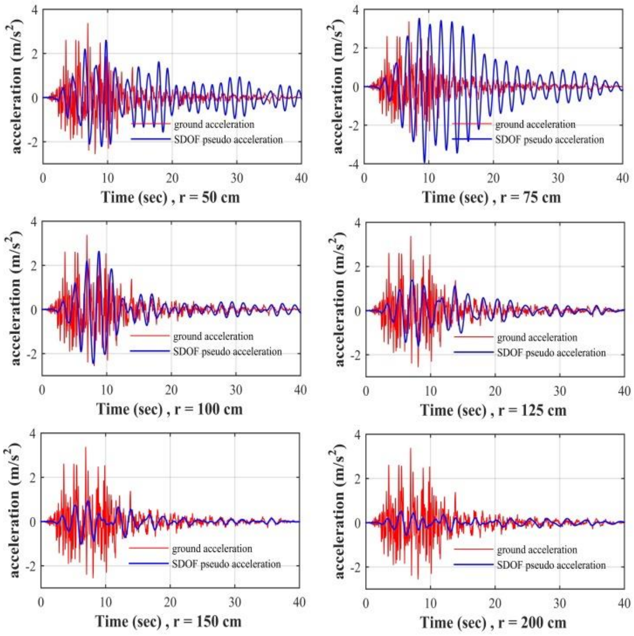
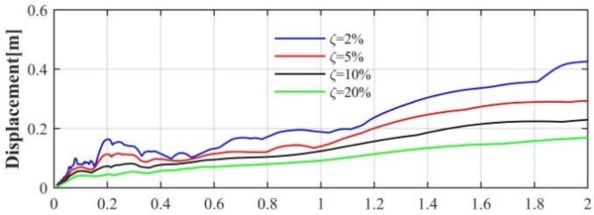
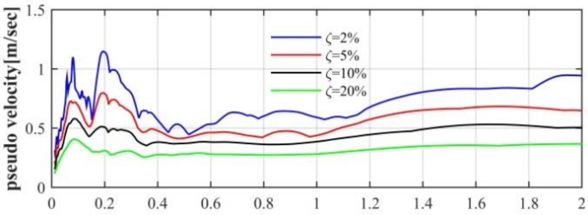


Fig. 9 Ground acceleration and pseudo-acceleration response time-history graphs in the isolated structure with different cable lengths under the Kobe earthquake with a damping ratio of 5%

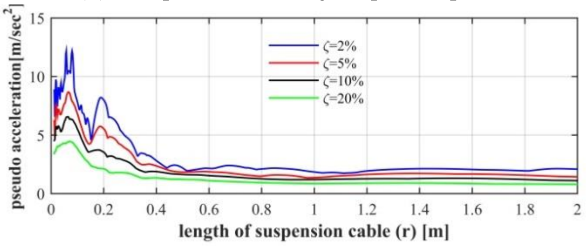
three mentioned earthquakes for the hanger cable length of 50, 75, 100, 125, 150 and 20 centimeters were plotted. By considering these figures, it is realized that the proposed system can reduce the acceleration in the structure subjected to all three studied earthquakes. This decrease in acceleration is raised by increasing the cable length; so that, the maximum decrease in acceleration was reached in the cable length of 200 cm. By studying the displacement



(a) The displacement response spectra

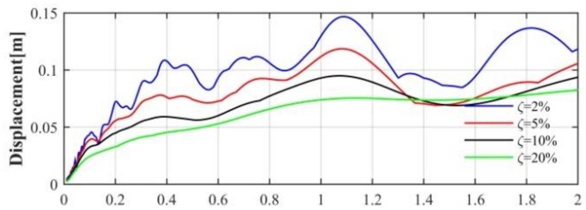


(b) The pseudo-velocity response spectra

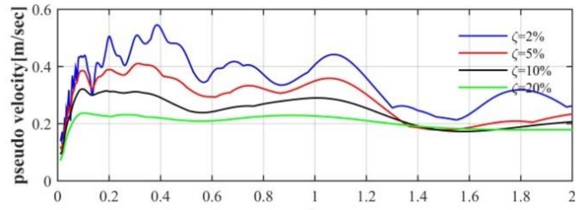


(c) The pseudo-acceleration response spectra

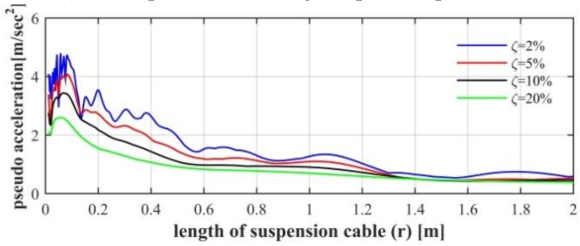
Fig. 10 Response of a SDOF system isolated by the proposed method, under the El Centro earthquake for different lengths of hanging cables with damping ratios of 2, 5, 10 and 20 %



(a) The displacement response spectra

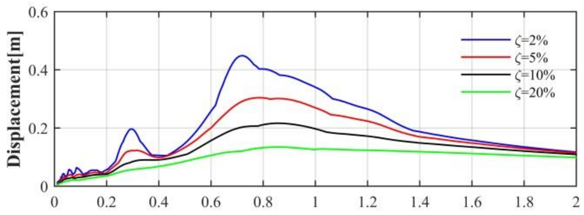


(b) The pseudo-velocity response spectra

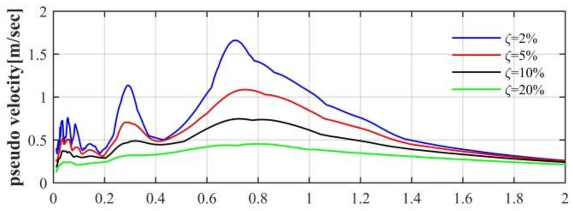


(c) The pseudo-acceleration response spectra

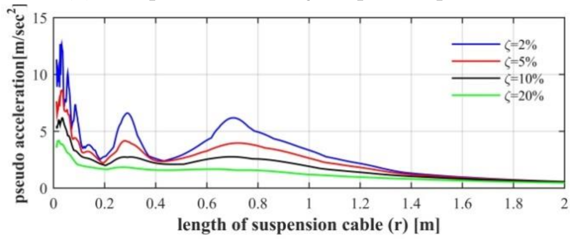
Fig. 11 Response of a SDOF system isolated by the proposed method, under the Chi-Chi earthquake for different lengths of hanging cables with damping ratios of 2, 5, 10 and 20 %



(a) The displacement response spectra



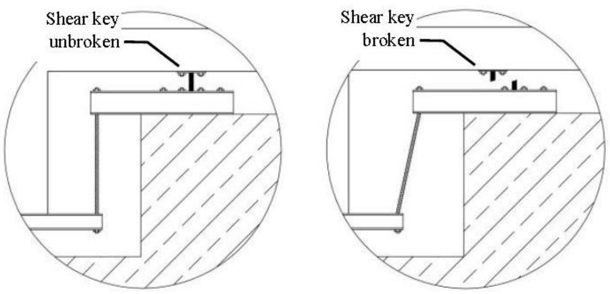
(b) The pseudo-velocity response spectra



(c) The pseudo-acceleration response spectra

Fig. 12 Response of a SDOF system isolated by the proposed method, under the Kobe earthquake for different lengths of hanging cables with damping ratios of 2, 5, 10 and 20 %

response spectra - plotted in Figs. 10(a)-2(a) - it was revealed that with the increase of the hung cable length, until about one meter, the maximum relative displacement amount of the structure is also increased. When the cable length exceeds one meter, the maximum relative displacement is gradually decreased and reaches to the ground maximum displacement. The maximum relative displacement in the structure during an earthquake is important in this regard that the amount of empty space between the columns and the pit wall must be greater than this amount; so that during the earthquake the columns do not collide with the pit wall. As it is seen from the graphs plotted in Figs. 10-12, when the damping ratio increases, the amount of displacement is reduced. As an example, for a cable length of 100 cm, the maximum displacements for a damping ratio of 2% were about 19, 13 and 34 cm in the El Centro, Chi-Chi, and Kobe earthquakes, respectively. While, when the damping ratio increased to 10% the maximum displacements were 12, 9 and 20 cm, respectively, which shows 58, 44 and 75 percent decrease in the maximum relative displacement. It represents the importance of damping in this system. By investigating the pseudo-acceleration response spectra (Figs. 10(c)-12(c)), it is realized that by increasing the length of the cable, the pseudo-acceleration response value after some fluctuations reaches to its maximum value and then by a further increase of the cable length it decreases. If a non-isolated ordinary SDOF structure was subjected to the three mentioned earthquakes, in the worst case, it might experience a maximum pseudo-acceleration equal to 1.2 g, 0.9 g, and 1.7 g for the El Centro, Chi-Chi, and Kobe earthquakes, respectively for a damping ratio of 2%, as it is seen in Figs. 4d-6d. While this amount can easily be reduced by the proposed system. In this system, if the cable length is taken less than half a meter (r<50 cm), the relative pseudo-acceleration response value will be a considerable amount. However, for the lengths of more than 50 cm, the pseudo-acceleration response of the structure reduces. For example, when r=50 cm is chosen, the maximum pseudo-acceleration response value, with a damping ratio of 2%, will be 0.22 g, 0.2 g and 0.29 g for the El Centro, Chi-Chi and Kobe earthquake, respectively. It shows that in this case, the maximum of pseudo- acceleration response value of the isolated structure is about one -fifth of the maximum of non-isolated one. This indicates a significant reduction in the amount of pseudo-acceleration experienced by the structure and also shows a very effective performance of the system. When r=100 cm is selected, the maximum pseudo-acceleration values in the structure will be, 0.19 g, 0.13 g, and 0.34 g, respectively for the three mentioned earthquakes. It shows a reduction in pseudo-acceleration for the El Centro and Chi-Chi earthquakes. However, there is a slight increase in the pseudo-acceleration values for the Kobe earthquake, which is due to the nature of that earthquake. If the cable length increases again, the pseudo-acceleration value for each of the three earthquakes will decrease and this decrease occurs in a gradual manner. Therefore, the more the length of the cable, the less the pseudo-acceleration value will be. It should be noted that as the length of the cable increases, the amount of relative displacement increases, which causes other problems. Regarding the graphs of the acceleration response spectra, for the four damping ratios of 2, 5, 10 and 20 percent (Figs. 10(c)-12(c)), it has been shown that with increasing the amount of damping ratio, the acceleration response of the structure decreases significantly. For example, if the damping ratio of the system increases from 2 to 10 percent, for the cable length of 100 cm, the structural accelerations for the El Centro, Chi-Chi, and Kobe earthquakes reduce from 0.19 g, 0.13 g, and 0.34 g to 0.12 g, 0.09 g, and 0.20 g respectively. It shows that the increase in damping ratio has a very effective role not only in controlling the relative displacement of the structure but also in reducing the acceleration transmitted to the structure. To create more damping in this system, various dampers can be used with this system, such as a viscous damper or steel bending bars. As can be seen from Figs. 10-12, the hanger cable length is the main determinant parameter of the proposed method, which has a direct influence on the structure's performance. In fact, these cables increase the natural period of the structure, so that by increasing the cable length, the period of the structure increases up to 3 seconds and more. In such a period, the effect of the earthquake on the structure is much less. The length of the cable affects inversely the pseudo-acceleration and relative displacement. When the cable length is less, the displacement response is low and the pseudo-acceleration response is high and when the cable length is high, the displacement response goes high and the pseudo-acceleration response becomes low. Moreover, displacement and pseudo-acceleration both decrease with



(a) before ground excitation (b) after ground excitation

Fig. 13 Shear key details before and after earthquake excitation

increasing the damping ratio, which shows the necessity of installing a suitable damping mechanism in this system. It is obvious that from a seismic behavior viewpoint, the acceleration response of a structure is more important than its relative displacement response.

Regarding the selection of suitable cable length, discussions have been made in more details in section 5.3, based on the characteristic period ranges of probable earthquakes and the optimum suspension cable length for each range has been suggested.

Because of this study, it is revealed that the proposed isolation method is very effective in reducing the effects of earthquakes on the structure.

5. Some additional discussion

In the following, some more details related to the proposed system, including the Service loading control, the effect of the vertical component of ground motion, the effect of the characteristic period of the earthquake, long-term function, practical feasibility, and advantages and limitations of the system were discussed.

5.1 Service loading control

Due to the fact that in the proposed seismic isolation system the structure is fully hanged from the foundation, it is probable that the structure vibrates during service or low lateral loads. To control the vibration against weak loads, it is necessary to have a proper mechanism to prevent the structure from moving in weak loads. This mechanism should act like a fuse and, in low loads, prevent the relative movement of the structure, but if the amount of force passes a certain limit, it releases the system and allows the vibration of the structure. This mechanism is also used in some other isolation systems and in different methods. A type of shear locking system is used in seismic isolation of bridges. Biao *et al*. (2018c) used a genuine steel rod in a study that could be used similarly in this system. In Fig. 13, the schematic of a similar shear key is proposed for this system. This shear key includes steel bars that connect the main structure to the foundation. The material of these bars should be completely brittle so that after a certain amount of shear force, it is broken and removed from the system. Obviously, the mechanical properties of shear key material

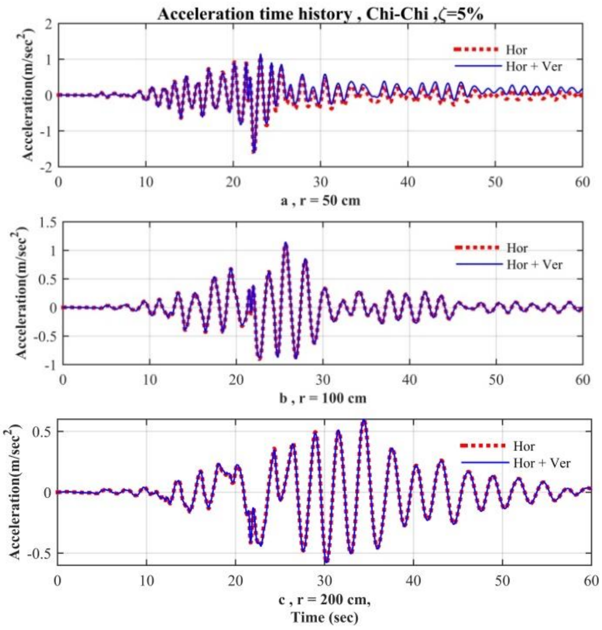


Fig. 14 Comparison of the pseudo-acceleration time history of the SDOF structure in two states, i.e., without, (Hor) and with, (Hor+Ver), the effect of vertical acceleration for the Chi-Chi earthquake with three lengths and damping ratio of 5%

and geometric dimensions and their number should be determined based on the design specifications of the seismic isolation system and the type and dimensions of the structure. In addition, the shear keys must have a replaceable type to be replaced in the case of failure and replaced with new ones.

5.2 Effect of the vertical acceleration on the system performance

Several researchers have studied the effect of the vertical component of ground motion on the seismic behavior of the isolation systems. Gordon *et al*. (2008), Biao Wei *et al*. (2018d) recently studied on the effect of vertical acceleration on the seismic performance of seismic isolators which were used in bridges. In this study, in order to investigate the effect of vertical acceleration on the performance of the proposed isolation system, by writing the MATLAB code, the effect of vertical acceleration was studied. For this purpose, the vertical acceleration of earthquake was accumulated with gravity acceleration and it was multiplied by the mass of the structure for the calculation of the structure's weight. In this case, the weight of the structure will be varied every time, and in the solution of the equation of motion, the weight of the structure will be variable and will be a function of time. In Fig. 14, the results for the two states i.e., without the effect of the vertical and with the effect of vertical acceleration for the Chi-Chi earthquake were plotted as an example. In these graphs, the response time history of the SDOF structure is plotted for 50, 100, and 200 cm suspension cable lengths and for the 5% of damping ratio. These graphs show that the effect of the vertical acceleration in the pseudo-

Table 2 Selected earthquakes for deferent characteristic period (*Tg*) ranges study

Record	RSN	*Ms*	*d* (km)	*Tg* (sec)
San Fernando, USA, 1971, CND-130	56	6.61	62	0.16
San Fernando, USA, 1971, FTJ-000	64	6.61	60	0.18
Tabas, Iran, 1978, FER-L1	140	7.35	90	0.19
Manjil, Iran, 1990, ABB-L	1633	7.37	12.5	0.26
Chi-Chi, Taiwan, 1999, TCU045-E	1485	7.62	26	0.29
Chi-Chi, Taiwan, 1999, TCU076-E.	1511	7.62	2.7	0.37
Lomaperita, USA, 1989, CAP-000	752	6.93	8.6	0.42
Tabas, Iran, 1978, TAB-L1	143	7.35	1.8	0.43
Kobe, Japan, 1995, KAK-90	1107	6.9	22.5	0.51
Bam, Iran, 2003, Bam-L	4040	6.6	2.	0.71
Chi-Chi, Taiwan, 1999, TCU067-E	1504	7.62	0.6	0.94
Kobe, Japan, 1995, TAK-000	1120	6.9	1.5	1.39

acceleration response time history of the structure is very slight and can be ignored. However, the effect of the vertical acceleration of the earthquakes used in this study on the seismic behavior of the proposed system is negligible.

5.3 Effect of uncertain characteristic periods of ground motions on the system performance

In this section, the effect of the characteristic period of earthquakes on the seismic behavior of the proposed system is evaluated. Each earthquake depending on the fault condition, soil properties, and distance from epicenter has a specific characteristic period. Some researchers investigated the effect of this parameter on the response of structures such as Biao Wei *et al*. (2018e). The characteristic period of an earthquake is defined as follows

$$Tg=2\pi\frac{EPV}{EPA} \tag{8}$$

In which EPV and EPA are the effective peak velocity and effective peak acceleration of earthquake respectively and are defined as follows

$$EPV=\frac{Sv}{2.5} \tag{9}$$

$$EPA=\frac{Sa}{2.5} \tag{10}$$

In which the *Sv* is the average spectral velocity of the ground motion between seconds 0.5 to 2.0 and *Sa* is the average spectral acceleration between seconds 0.1 to 0.5 of the earthquake duration, for a damping ratio of 5%. According to the Japanese code (1980), the site and corresponding earthquakes are classified into four categories. Type I: rock and hard soil *Tg*<0.2 sec, Type II: hard soil 0.2<*Tg*<0.4, Type III: medium soil 0.4<*Tg*<0.6, and Type IV: soft soil *Tg*>0.6 sec. For each *Tg* range, three earthquakes and in a total of 12 records were selected. The

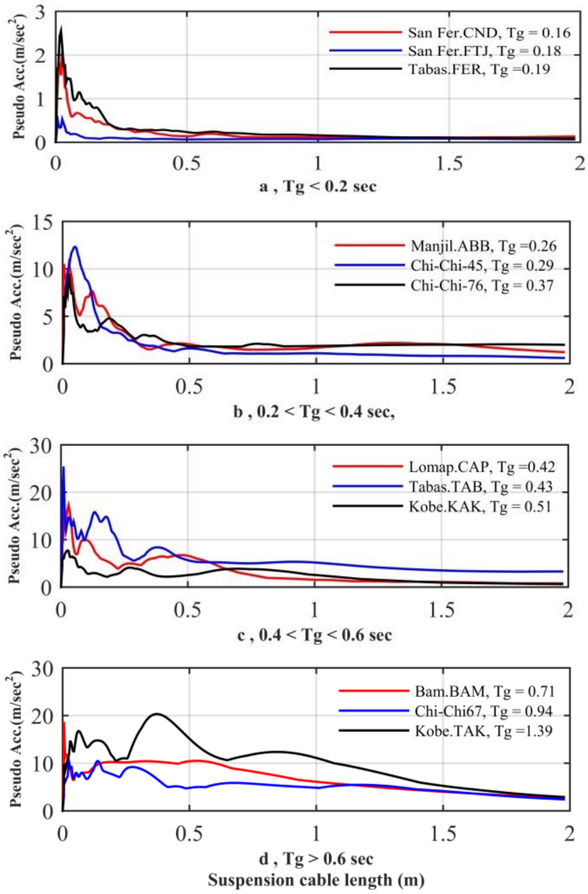


Fig. 15 The pseudo-acceleration response spectrum for different ranges of the earthquake characteristic period (*Tg*), (a) *Tg*<0.2 sec, (b) 0.2<*Tg*<0.4, (c) 0.4<*Tg*<0.6 and, (d) *Tg*>0.6 sec, damping ratio of 5%

characteristics of these earthquakes are listed in Table 2. Structural responses of a SDOF structure isolated with the proposed system under these earthquakes were obtained as pseudo-acceleration response spectrums using MATLAB coding and were shown in Fig. 15.

Fig. 15 shows the response of the structure for the four groups of the characteristic period of the earthquake. The horizontal axis of this figure shows the length of the pendant cable of the proposed system and the vertical axis shows the maximum pseudo-acceleration of the structure. As seen from this graph, the proposed system is effective in all characteristic period ranges and is able to reduce the amount of the earthquake acceleration transmitted to the structure by increasing the length of suspension cable. It should be noted that the behavior of the system is not the same in all groups. In groups with the shorter characteristic periods, the amount of pseudo-acceleration can be controlled by less cable length, whilst moving towards the longer characteristic period, it is necessary to use longer suspension cable to keep the system performance up. Based on this graph, an optimum suspension cable length can be suggested for each range. Accordingly, for the first range, the length of the cable of 40 cm, for the second range 60 cm, for the third range 80 cm and for the fourth range, 120 cm can be used.

5.4 Long-term functioning of the system

In order to achieve the expected performance at any time, a proper isolation system must have good performance over the lifetime of the structure. The proposed system in this study has a simple mechanism, which is one of the advantages of it. This system is a passive system and if it is not damaged, it can function reliably. A pendant cable is connected to the top of the foundation from one side and to the bottom of the columns of structure on the other side and in fact, it is a simple part of the structure likes the other main components, such as the beam or the column of the structure. However, due to the importance of its operation, it is necessary to inspect and control over the lifetime of the structure. Pendant cables are tensile members which bear the weight of the structure. Their performance is almost like to the tensile cables on suspended bridges. These cables should be made of suitable and durable material, and after implementation, it is necessary to protect them from the environment hazardous conditions and also prevent from possible corrosion and rust in order to eliminate the reduction of their tensile strength. To do this, it is necessary to insulate the isolation holes and in order to prevent moisture from entering and prevent the loss of waste material into the hole over the lifetime of the structure; a flexible cover should be placed on the top of holes.

A complementary idea to avoid permanent tension of cables over the lifetime of the structure can be achieved in the same way as Tsai *et al*. (2010) have proposed. They invented an isolation system for sensitive and expensive devices. In the system, a central metal ball is placed inside a concave surface that slips during the lateral vibration, causing the seismic isolation. In addition to this ball, there are four side balls in the system, which, in the case of the motionless state they incorporate in the bearing of the vertical load, causing the load not to be concentrated at a single point and distributed in more points. In the proposed isolation system, if the appropriate shear keys are used, in the motionless state, shear keys will bear part of the gravity load and there will be less tensile forces in cables.

5.5 The practical feasibility of the system

To implement this isolation system, it is necessary to carry out a series of executive tasks in the structure. During the foundation's implementation, appropriate pits should be created in the location of the columns within the foundation with appropriate molding. The depth of the pits is proportional to the length of the pendant cable and should be taken more than that. The width of the hole should be considered in accordance with the dimensions of the columns. For example, if the dimensions of the column are 30 cm and we want to give a 20 cm freedom of movement to the structure, the dimensions of the holes should be 120×120 cm. At the top of the holes, suitable steel support should be installed in consoles. The length of the console must be in accordance with the length of the motion required. For example, if the lateral movement of the columns is 20 cm, the length of the console should be about 25 cm. An additional 5 cm is considered for mounting the hanger cable. The console retainer can be made of steel profile and should be designed according to the load applied to the structure; so that it has dimensions suitable for shear and bending created in the support. It is possible to use the I-shaped double-clamped profile for this purpose so that by creating holes on the flange of the profile at the end of the console, the cable can easily be connected to the profile. It is necessary that the steel support is continued throughout the foundation and is connected to the foundation by threaded bolts which they have already been laid in the foundation.

In the structure, it is necessary to make the appropriate requirements at the end of the columns to install the pendant cable. To do this, just like the base plate on the steel structures, the appropriate steel plate at the end of the column should be connected. Dimensions of this plate will also be appropriate to the dimensions of the column and the amount of freedom of movement required. For example, if the dimensions of the columns are 30 cm and the freedom of movement is 20 cm, the dimensions of the plates should be about 80 cm. At each cable's location, holes are made on the base plate, and the pendant cables cross the holes and are screwed on the other side. Obviously, the thickness of the steel plate should be in accordance with the structure's load, and it uses stiffener plates for flexural strengthening.

The number and diameter of the suspension cables are determined based on the size of the building and the loads applied. Both ends of the pendant cables are required to be screwed so that it can be connected from one side to the top of the foundation and from the other side to the end of the column. To do this, a longitudinal hole can be made inside the steel screw, and the cable can pass through from on each end of cable and screw can be pressed, so the two ends of the cable are screwed. By doing this, the screw is locked to the cable and the cable hanger has two ends of the screw and can easily be connected. Screwing the two ends of the pendant cable helps to adjust the length of the cable by tightening the nut and eliminating the loosening of some cables. After installing the columns of the first story, ground-level beams are also attached to the columns and a stable frame is created. After that, the construction of the structure is continued according to a conventional structure. As with other seismic isolation systems, it is necessary to use a suitable floor to separate the foundation from the upper structure so that the lateral movement of the structure can be done freely. This floor can be constructed slightly above the foundation (e.g., 50 cm above the foundation). The distance between the this and the foundation will be a suitable place for mounting the damper, which can be connected to the foundation in one side and to the structure on the other side in accordance with Fig. 1.

5.6 Advantages and limitations of the system

The seismic isolation system introduced in this paper (SCSI) has some advantages and limitations compared to the other conventional isolation methods. The following relative advantages can be mentioned for this system:

1. Because of the absence of any friction force or other anti-restoring forces in the proposed system unlike other isolation systems, there will be no permanent displacement

in the structure after an earthquake, and the structure returns to its initial position after vibration.

2. The natural frequency of the system is easily adjustable by changing the length of the hanger cable.

3. The lateral stiffness of the proposed system is nonlinear and as the relative displacement increases, the stiffness of the system increases as well. This characteristic leads to limited relative displacements in the structure during severe ground excitations.

4. The technology of construction of the proposed system is easier than most of the conventional isolation methods.

5. Because of the simplicity of the system, the service and maintenance are easier than other similar systems.

6. There will be almost no change in the performance level of the system over the lifetime of the structure.

7. Repetition of earthquakes does not destroy the system and it does not need to be replaced. In other words, this system is not damaged in earthquakes.

The following limitations can be stated for this system:

1. This isolation system has low damping capacity and it is necessary to apply an additional damping mechanism to the system in order to dissipate more energy and reduce relative displacements.

2. To handle larger relative displacements, the system requires wider and deeper holes in the foundation that is limited by the thickness of the footing.

3. The use of this system in frame structures especially steel structures is easier than other building types. For instance, some additional considerations should be taken into account regarding the application to concrete frame structures.

6. Conclusions

In this research, a new system of seismic isolation for buildings so called - the Suspended Columns for Seismic Isolation in structures (SCSI) - is introduced. In this system, some pits are created inside the foundation and the structure is suspended in the holes through pendant cables. The cable hung from the top of the pits and connects the column to the foundation so that the columns become suspension and the whole structure acts as a suspension mass. In this method, during an earthquake, the foundation of structure moves, but this movement is transferred to the columns just as a reduced amount. In fact, the structure moves to sides like a clock pendulum and the ground acceleration is transmitted to the structure very slightly. The main parameter in the controlling of the applied acceleration to the structure is the cable length so that the acceleration response amount of the structure can be justified by appropriate selecting of the pendant cable length. The details of the system, including the number and diameter of the cables, should be calculated and constructed based on the weight of the structure. To study the seismic performance of the proposed method, the equation of motion of the isolated structure was written and solved by means of Matlab code. The equation of motion was solved for the El Centro, Chi-Chi, and Kobe earthquakes. The analysis results were shown as the relative displacement response and pseudo-acceleration spectra. The results of the study show that this method is quite effective for reducing the effect of the earthquake on the structure, and it significantly reduces the amount of acceleration transmitted to the structure. The longer the cable length is, the lesser the amount of acceleration transmitted to the structure, while as the length of the cable increases, the amount of displacement response of the structure also increases. In the study, the impact of damping on the seismic performance of the isolated structure has also been investigated. The results indicate that increasing the damping coefficient of the system significantly reduces both the relative displacement and pseudo-acceleration response of the structure, indicating the necessity of using suitable dampers in this isolation system.

Moreover, for controlling the structure against the weak lateral loads, a shear key system was used and discussed. In addition, the effect of the vertical component of earthquakes on the seismic performance of the proposed isolation system was also investigated. It was realized that the vertical acceleration has an ignorable effect on the seismic performance of the system. The performance of the system in a variety of the characteristic period ranges of earthquakes was also investigated and the optimum length of the suspension cable was suggested for each period range. Also, the long-term serviceability of this system has also been discussed and measures were considered for handling the possible problems. Some aspect of the practical feasibility of the system was also discussed. Finally, the advantages and limitations of the proposed system were discussed and compared with the previous seismic isolation methods.

In order to evaluate and validate the results of the theoretical study conducted in this paper, a series of laboratory experiments have been planned to be carried out as the next phase of the research work.

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