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Mitigation of the seismic response of a cable-stayed bridge with soil-structure-interaction effect using tuned mass dampers

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Abstract. A cable-stayed bridge (CSB) is one of the most complicated structures, especially when subjected to earthquakes and taking into consideration the effect of soil-structure-interaction (SSI). A CSB of a 500 m mid-span was modeled by the SAP2000 software and was subjected to four different earthquakes. To mitigate the harmful effect of the vibration generated from each earthquake, four mitigation schemes were used and compared with the non-mitigation model to determine the effectiveness of each scheme, when applying on the SSI or fixed CSB models. For earthquake mitigation, tuned mass damper (TMD) systems and spring dampers with different placements were used to help reduce the seismic response of the CBS model. The pylons, the mid-span of the deck and the pylon-deck connections are the best TMDs and spring dampers placements to achieve an effective reduction of the earthquake response on such bridges.

Keywords: cable-stayed bridge; soil-structure-interaction (SSI); tuned mass damper (TMD); spring damper; seismic response; nonlinear analysis

1. Introduction

Bridges are the most common way to transport the traffic within an unsuitable topography, and a cable-stayed bridge (CSB) is one of the most suitable bridge types to perform that task, because of its unique configuration, fast progress in construction and high efficiency. A cable-stayed bridge (CSB) is one of the most efficient structures for transporting traffic between long distance spaces without big supports (just two point supports), and high-performance under static and dynamic loads. The first main components of these structures is the deck (steel or RC sections) and the pylons (the main supports of the deck which is connected to the cables), while the second important component in a CSB are the cables which are the most effective elements and the factor that controls the static and dynamic response of the CSB, where the diameter and the length of the cables have a great effect on the response of the cables under static and dynamic loads. The most effective loads on a CSB are the wind and earthquake loads, the effect of these loads will change the response of the CSB with the change of response of the cables and when the SSI effect contributes to the foundations of the pylons and the end supports of the CSB, the response of the CSB will perform as nonlinear behavior for every element of the bridge in addition to the nonlinear response of the soil. The combination of the nonlinear response of the CSB and soil under earthquake loads will give the maximum straining actions in the CSB, so passive devices will be used to mitigate the seismic response of the CSB.

Wang and Yang (1996) studied numerically the nonlinearity parameters effect on cable-stayed bridges (CSBs) and found that in the initial shape analysis the cable sag effect is most important; while in the static deflection analysis, the large deflection effect is the most significant, the beam-column effect is important, and the cable sag effect becomes the least important one.

Karoumi (1999) studied the dynamic effect of moving vehicles on cable-stayed bridges and suspension bridges and concluded that the roughness of road affects the dynamic response and that utilizing the dead load tangent stiffens matrix, the linear dynamic traffic load analysis gives sufficiently accurate results.

Davalos (2000) illustrated the structural behavior of cable-stayed bridges under different load cases and different control devices and concluded that the number and configuration of the cables, the geometric proportions (height of the tower, ratio between the tower height and the dimension of the central span), the support conditions and the stiffness of the structural elements are the most effective parameters of the response of a CSB.

Khan *et al.* (2004) carried out a probabilistic risk analysis (PRA) of a cable-stayed bridge (CSB) subjected to earthquake taking into consideration SSI; it was shown that the flexible base provides significantly less value of probability of failure as compared to the fixed base and the properties of ground motion significantly affect the probability of failure of a CSB.

Camara and Astiz (2011) studied the seismic response

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of cable-stayed bridges (with different types of towers, cable arrangement, main span length and type of foundation soil) subjected to a set of twelve synthetic accelerograms, and they concluded that CSBs with two planes of cables are more recommended, while pylons for which the lower segments are connected to a single vertical element may dangerously concentrate the seismic demand, and the transverse component of the accelerogram record is the most demanding one which imposes the use of seismic devices instead of the traditional rigid transverse connection between towers and deck.

Zhang and Wu (2011) performed a detailed dead load stage analysis of a cable-stayed bridge (CSB) where the optimization method of unknown load factor is used to determine the cable forces to achieve an ideal state and concluded that their method leads to optimal structural performance for the CSB and might be useful for the design of other similar bridges.

Choi *et al.* (2012) proposed a new procedure to estimate more accurately the total tension force in the cables of a cable-stayed bridge (CSB) which can be effectively used in structural health monitoring for such structures, by taking into consideration the initial tension result from the initial deflection of the cable and the stretching force induced by the initial curvature shortening.

Valdebenito *et al.* (2012) carried out a comparative seismic analysis of the response of cable-stayed bridges for different stay cable arrangements and concluded that the response spectrum analysis can be employed only as a first approach of the seismic response of cable-stayed bridges, while the nonlinear time history analysis is mandatory for the design and accurate analyses.

Kuyumcua and Ates (2012) investigated the stochastic responses of a cable-stayed bridge subjected to the spatially varying earthquake ground motion by the finite element method (FEM) considering the soil-structure interaction (SSI) effects and concluded that in case of rigid towers and soft soil condition, the SSI should be significantly considered for the design of such bridges.

Abdel Raheem *et al.* (2013) studied the nonlinear static behavior of cable-stayed bridges and investigated some important design parameters such as the cross-section of cables, the cable layout (either fan or harp pattern), the pylon height to span ratio and the mechanical properties of the deck and pylon.

Abdel Seed *et al.* (2013) studied the non-linear dynamic behavior of cable-stayed bridges under seismic loadings. The geometric nonlinearity comes from the cable sag effect, axial force-bending moment interaction and large displacements. These authors found that the cross sections of the cable system and the pylon height to span ratio are the most important parameters affecting the reduction of the dynamic response of CSBs, and the harp system is preferable in order to reduce the acceleration response of the pylon.

Geng *et al.* (2014) created a 3D FEM model to study an existing long multi-span cable-stayed bridge and their results indicated that the structural system measures of the multi-span cable-stayed bridge have a great effect on the dynamic properties, which deserves special attention for the seismic design and wind-resistant design of the multi-span cable-stayed bridge.

Xu *et al.* (2014) presented an alternative seismic design strategy for cable stayed bridges with concrete pylons when subjected to strong ground motions and they compared a conventional seismic design using supplemental dampers with the proposed strategy using nonlinear seismic design of pylon columns.

Ni *et al.* (2015) presented a feasibility study on the structural damage alarming and localization of long-span cable-supported bridges using multi-novelty indices formulated by monitoring-derived modal parameters.

Zhang and Yu (2015) investigated the seismic response of a cable-stayed-suspension hybrid bridge with a main span of 1400 m under horizontal and vertical seismic excitations by the response spectrum analysis and time history analysis and compared to the cable-stayed bridge and suspension bridge with the same main span.

Salamak *et al.* (2016) compared selected experimental techniques to measure the deck and pylon displacements for a CSB under dynamic loads and concluded that that best method is non-contact measurements like the interferometric radar.

Kim and Kang (2016) investigated the change of the structural characteristics of steel cable-stayed bridges after cable failure and concluded that significant change of the structural behavior and ultimate capacity occurs even if just one cable fails.

Elias and Matsagar (2017) investigated the effectiveness of TMDs in the seismic response control of isolated RC bridges including soil-structure interaction and observed that the soil surrounding the pier has significant effects on the bearing displacement of the isolated RC bridges, and that the seismic responses of the isolated RC bridge reduced significantly with installation of the TMDs.

Xiu *et al.* (2017) investigated experimentally the wind-resistant performance of seismic viscous dampers on a cable-stayed bridge and found that the CSB exhibits good wind-resistant performance, while the seismic viscous dampers have very minor effects on the vertical buffeting displacement of the mid-span girder, and thus for a long span CSB the seismic design and wind-resistant design can be done separately.

Lu *et al.* (2017) proposed an effective design approach for Multiple Tuned Mass Dampers (MTMDs) in pedestrian bridges by utilizing the transfer function to obtain each TMD's optimum stiffness and damping and concluded that MTMDs designed through this proposed method can significantly reduce the structural response when subjected to pedestrian excitation.

Kahya and Araz (2017) presented the series multiple tuned mass dampers (STMDs) to suppress the resonant vibrations of railway bridges under the passage of high-speed trains (HSTs) and their results showed that the STMDs are effective in bridge vibration suppression.

Camara (2018) reviewed the seismic behavior of cable-stayed bridges, which present complex interactions between their structural elements (towers, cables, deck, foundation), reduced damping and slenderness. The author presented the current design trends in the seismic design and the control

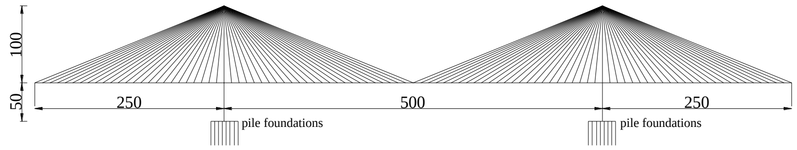
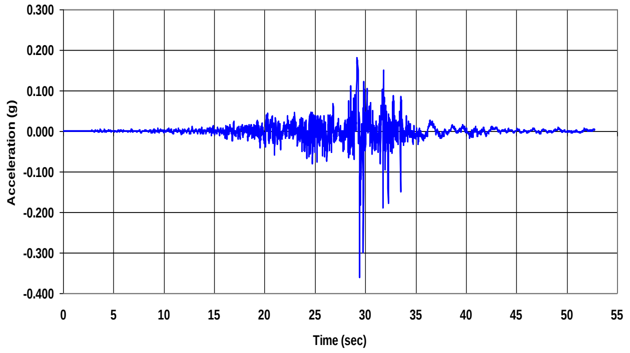
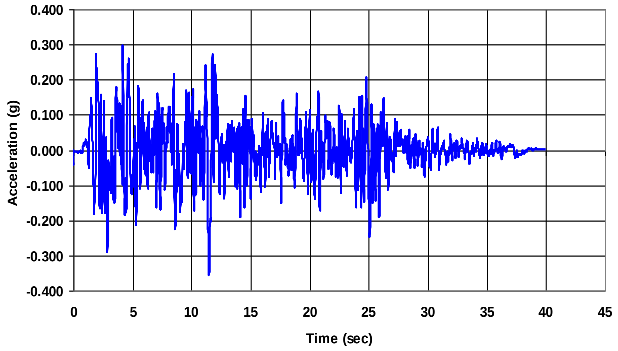


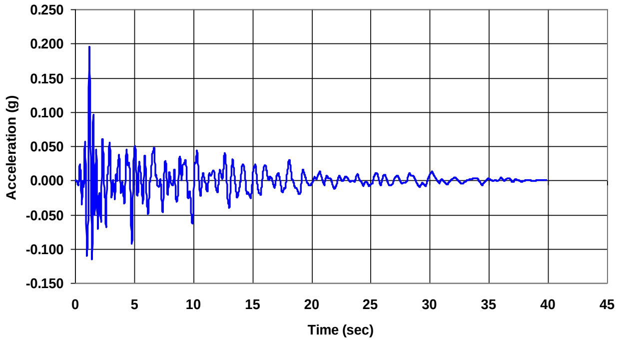
Fig. 1 CSB model with pile foundations (considering SSI effect)



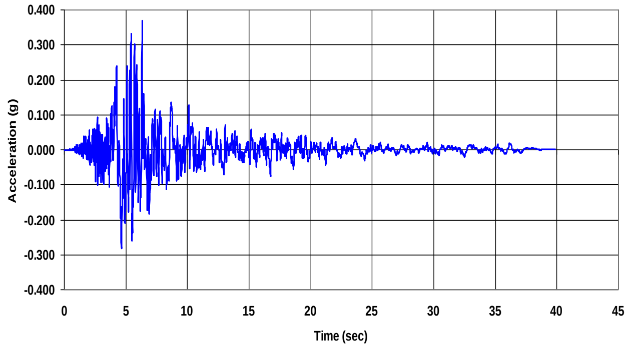
(i) Chi-Chi



(ii) El Centro

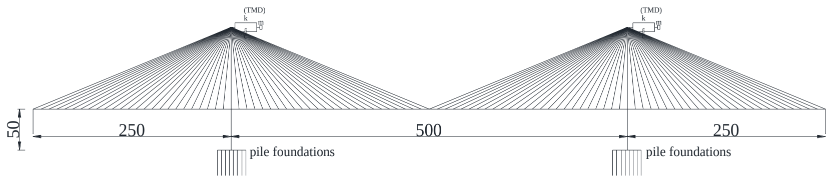


(iii) Hollister

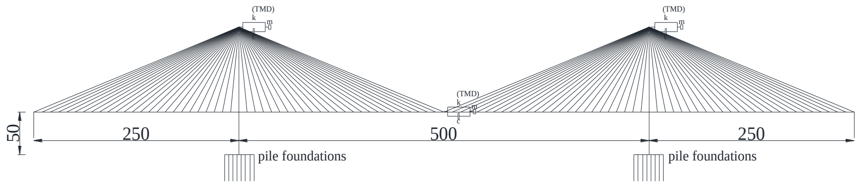


(iv) Loma Prieta

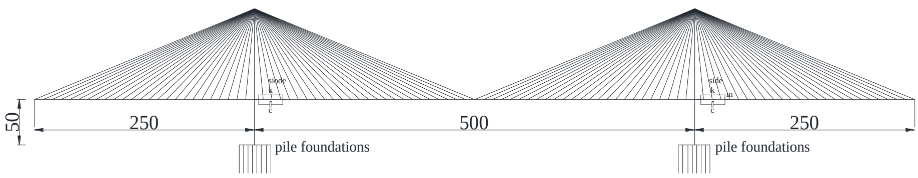
Fig. 2 Earthquake accelerograms



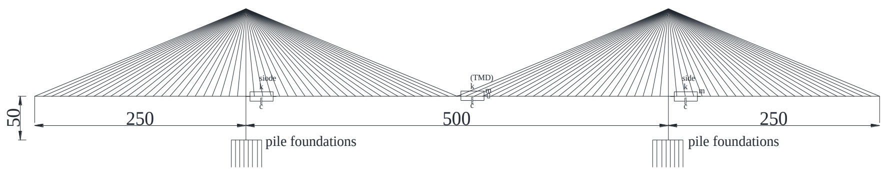
(i) 2 TMDs at the top of each pylon (i.e., 4 TMDs in total)



(ii) 2 TMDs at the top of each pylon + 2 TMDs at the mid-span (i.e., 6 TMDs in total)



(iii) 2 side spring dampers for each pylon (i.e., 4 spring dampers in total)



(iv) 2 side spring dampers for each pylon + 2 TMDs at the mid-span (i.e., 4 spring dampers & 2 TMDs in total)

Fig. 3 Four mitigation schemes

of cable-stayed bridges.

A cable-stayed bridge (CSB) is one of the most effective structures used to transport the traffic between a long-distance span. A CSB with a mid-span of 500 m and two side spans of 250 m is used to investigate the mitigation system of dampers that ensures the seismic response of the structure considering the effect of SSI, where the support of the pylons is founded on piles caps taking into consideration the soil-pile-structure interaction.

2. Model description

Fig. 1 shows the model of a 500 m mid-span CSB, where each of the two side spans has a length of 250 m. The deck width is 18 m with steel cross-section beams (built up section with height 2500 mm), the deck height from the foundation level is 50 m, the X-girder is repeated each 10 m in x direction, and the main girder is repeated each 6 m in y direction, the pylons (towers) are spaced 500 m and the total height of the pylons is equal to 150 m from the foundation level while their height from the deck level is 100 m, the cross-section of the pylons is box reinforced concrete with thickness 1 m with dimensions 25 m×25 m from foundation level until deck level and with dimensions 15 m×15 m from deck level until the top of the pylons. The cables are chosen as strand steel kind of St56 and their diameter is 200 mm for the outer cables and 100 mm for the inner cables. The foundations of the two towers are made of pile caps supported on piles, and for the end supports the foundations are made of piles.

3. Loads and earthquakes

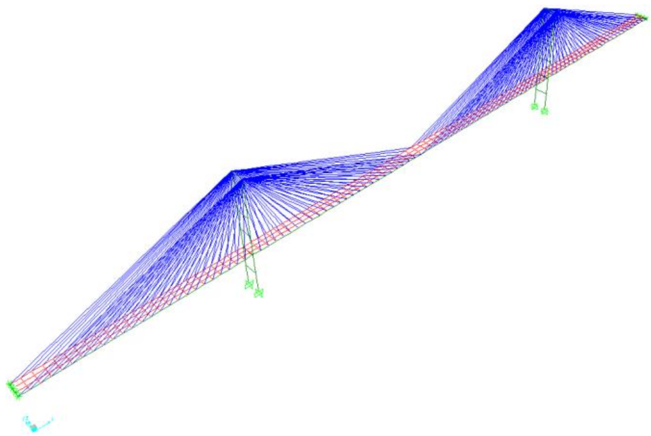
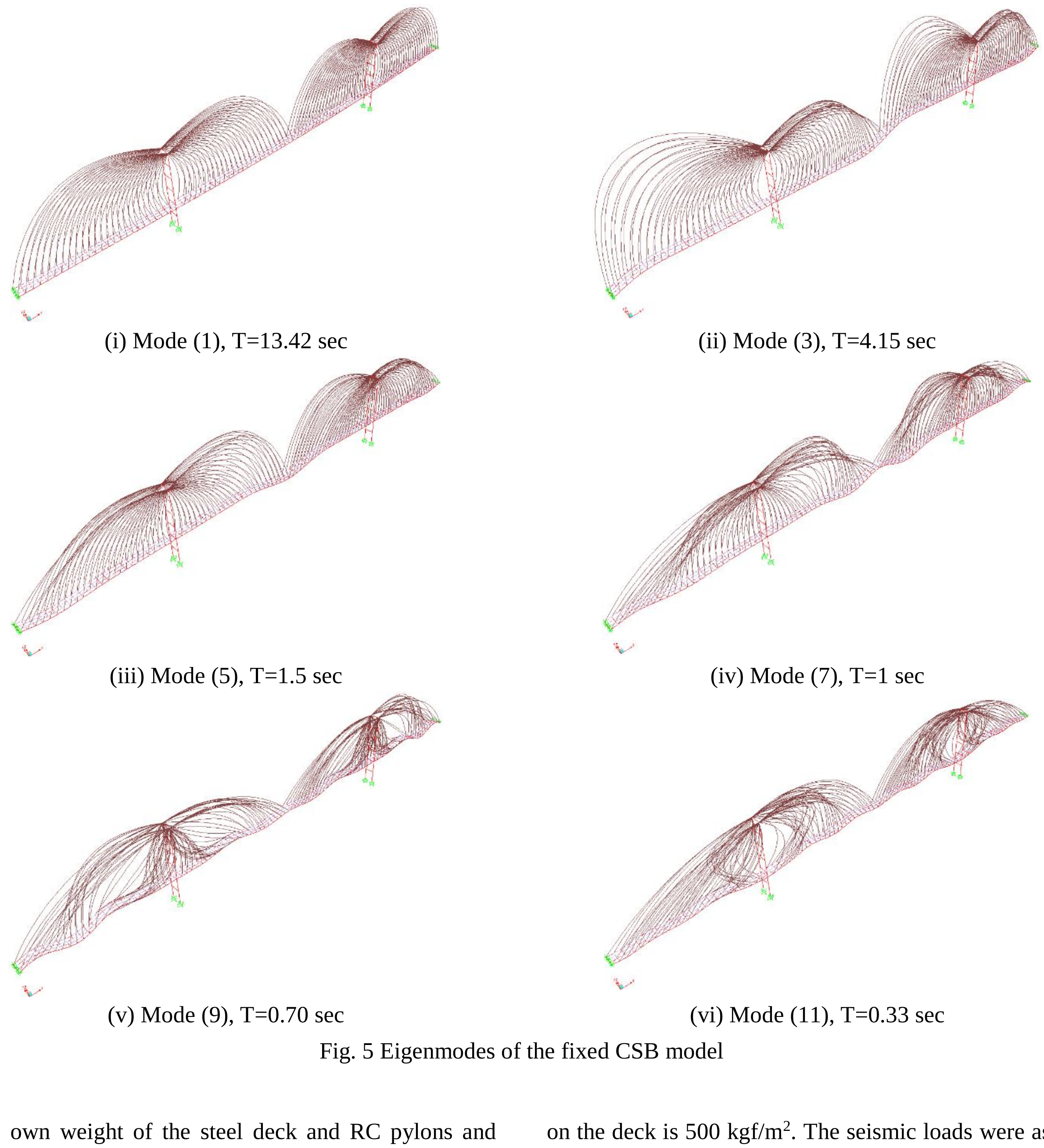


Fig. 4 The 3D fixed model of the CSB



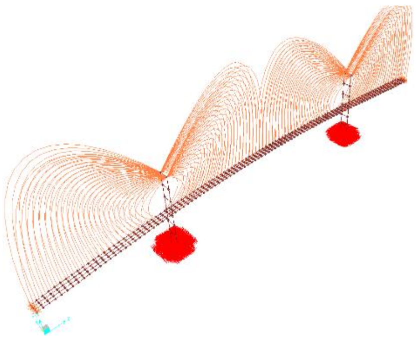
(i) Mode (1), T=13.42 sec (ii) Mode (3), T=4.15 sec

(iii) Mode (5), T=1.5 sec (iv) Mode (7), T=1 sec

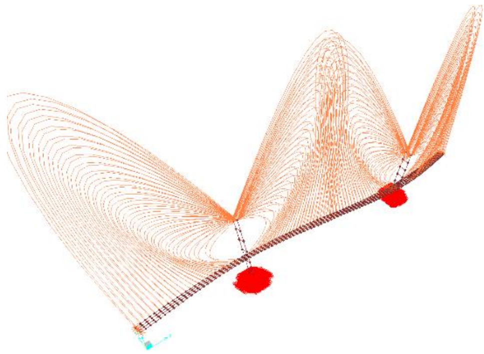
(v) Mode (9), T=0.70 sec (vi) Mode (11), T=0.33 sec

Fig. 5 Eigenmodes of the fixed CSB model

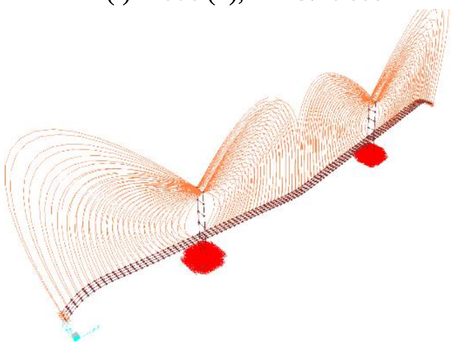
The own weight of the steel deck and RC pylons and cables is calculated by the SAP2000 V17 software on the basis of the true weights of these elements, and the live load on the deck is 500 kgf/m^2. The seismic loads were assumed to act in x and y directions with the same intensity. The used earthquake accelerograms (Fig. 2) are of the 1999 Chi-



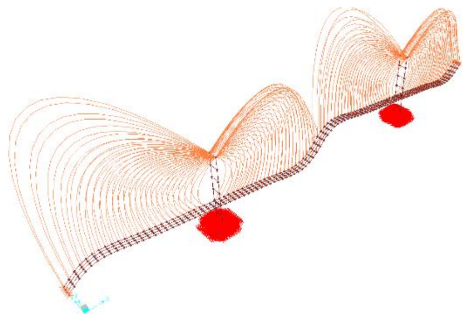
(i) Mode (1), T=13.16 sec



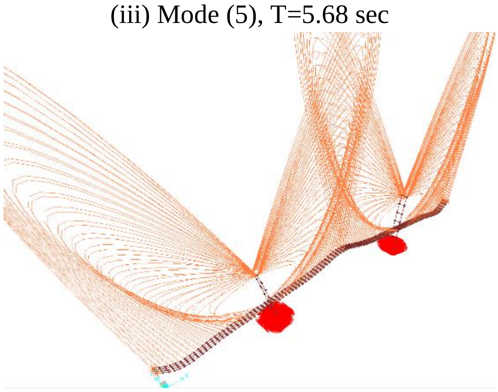
(ii) Mode (3), T=6.7 sec



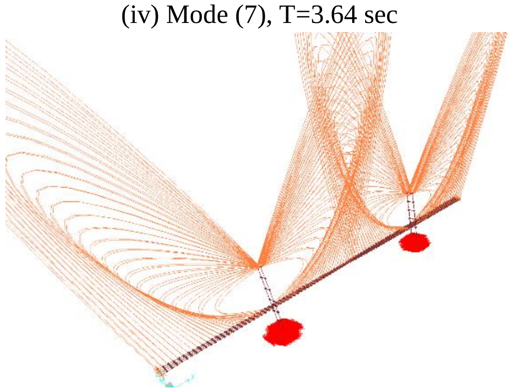
(iii) Mode (5), T=5.68 sec



(iv) Mode (7), T=3.64 sec



(v) Mode (9), T=2.22 sec



(vi) Mode (11), T=2.14 sec

Fig. 6 Eigenmodes of the SSI CSB model

Chi earthquake that occurred in Taiwan with magnitude 7.6, the 1940 El Centro earthquake that occurred in the Imperial Valley in south-eastern Southern California with magnitude of 6.9, the 1974 Hollister earthquake that occurred near the central California with magnitude 5.2, and the 1989 Loma Prieta earthquake that occurred in Northern California with magnitude of 6.9.

4. Mitigation schemes using tuned mass dampers

The use of Tuned Mass Damper (TMD) in mitigation of the seismic response of a CSB subjected to earthquakes is a useful tool but the TMDs must also be placed in those specific locations in the CSB which have the maximum straining actions in order to achieve the maximum mitigation effect of earthquakes. When a CSB is subjected to an earthquake, the parts of the CSB mostly affected by the earthquake are the pylons (towers), the pylon-deck connections and the mid-span of the deck.

In this study, the following four mitigation schemes (Fig. 3) are investigated:

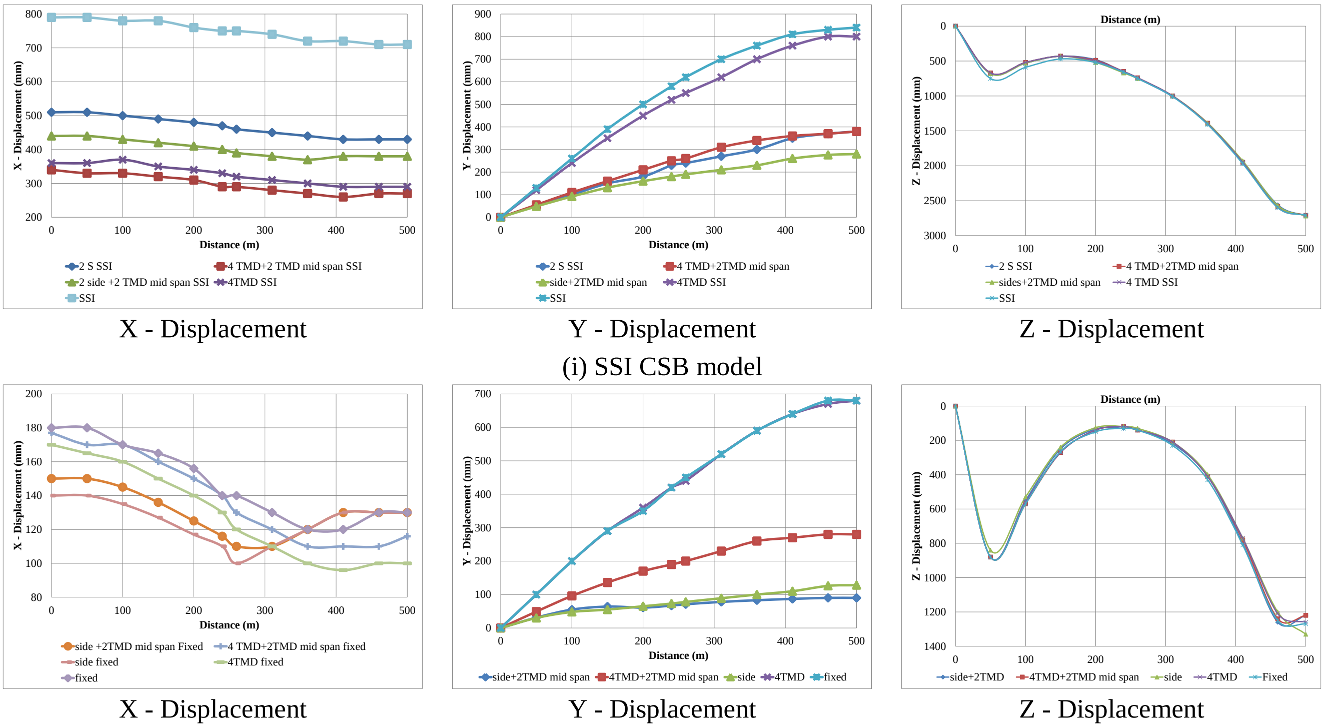
The first mitigation scheme (Fig. 3(i)) uses 2 TMDs at the top of each pylon, i.e., 4 TMDs in total.

The second mitigation scheme (Fig. 3(ii)) uses 2 TMDs at the top of each pylon and 2 TMDs at the mid-span of the deck (one at each side of the deck), i.e., 6 TMDs in total.

The third mitigation scheme (Fig. 3(iii)) uses 2 side spring dampers for each pylon located at the connection of each pylon with the deck (the spring dampers are connected between each pylon and the deck), i.e., 4 spring dampers in total.

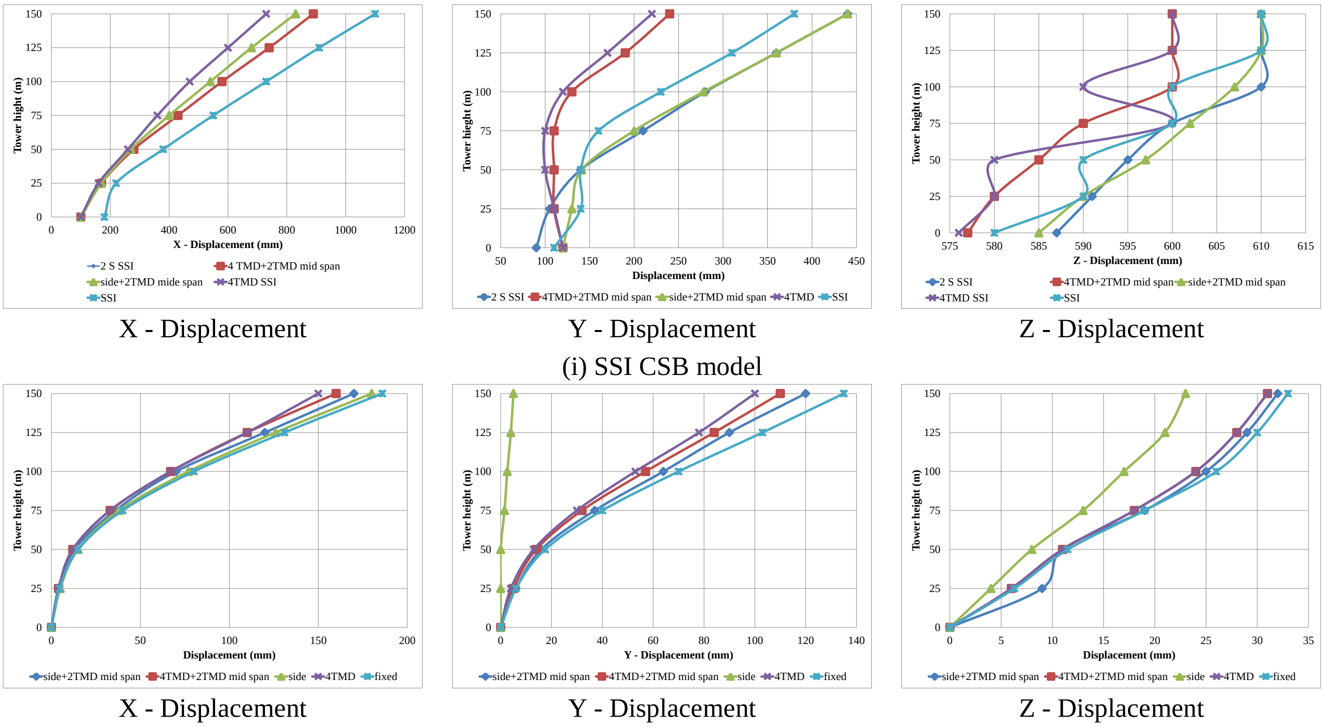
Finally, the fourth mitigation scheme (Fig. 3(iv)) uses 2 side spring dampers for each pylon located at the connection of each pylon with the deck and 2 TMDs at the mid-span of the deck, i.e., 4 spring dampers and 2 TMDs in total.

All above mitigation schemes are applied on both the fixed and SSI models and are compared with the non-mitigation cases (i.e., without dampers) to show the effect



(ii) Fixed CSB model

Fig. 7 Deck displacements under the Chi-Chi earthquake



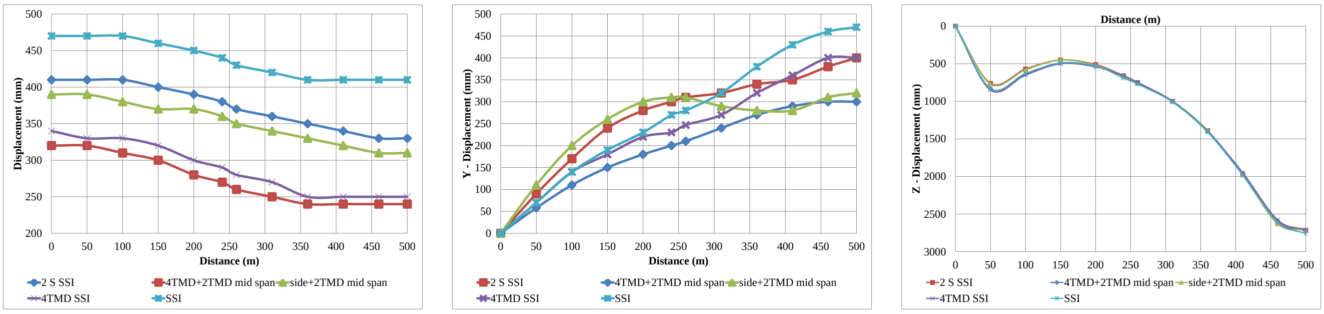
(ii) Fixed CSB model

Fig. 8 Tower displacements under the Chi-Chi earthquake

of the four mitigation schemes and investigate which one will be the most effective in the mitigation of earthquakes.

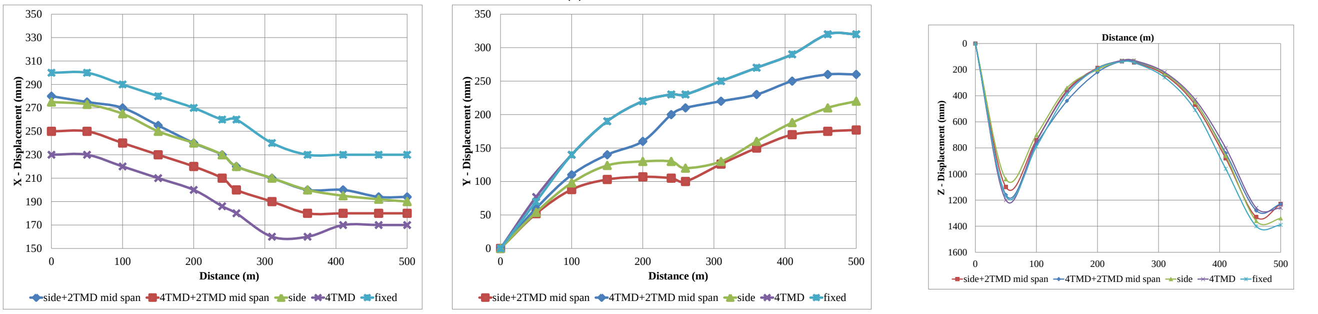
5. Results and discussion

Two nonlinear 3D CSB models are used in SAP2000 V.17 to show the seismic response of the CSB, without SSI (fixed model) and with the effect of SSI (SSI model). In order to mitigate the dynamic response of the CSB, four mitigation schemes of dampers are used to show which is



X - Displacement Y - Displacement Z - Displacement

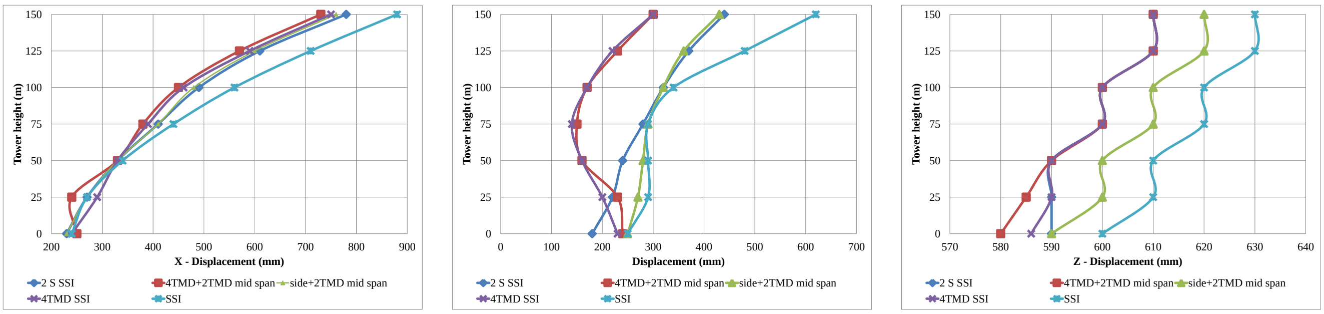
(i) SSI CSB model



X - Displacement Y - Displacement Z - Displacement

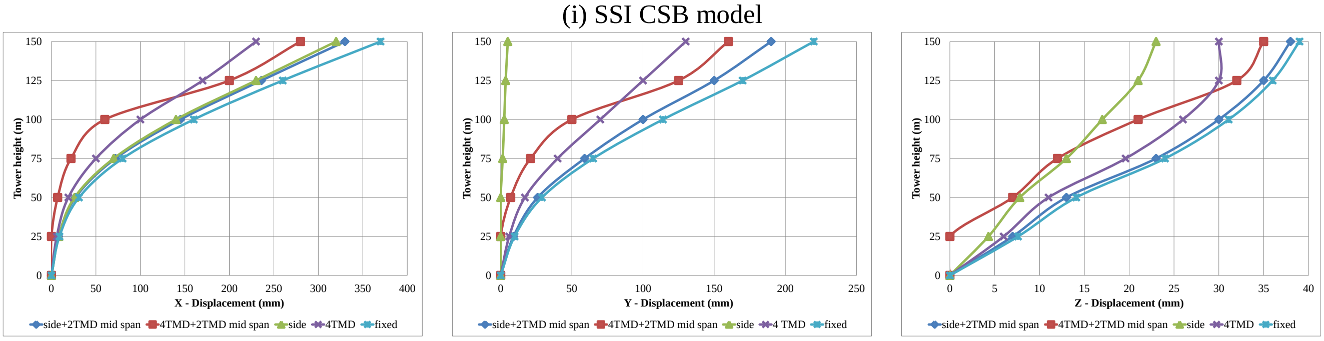
(ii) Fixed CSB model

Fig. 9 Deck displacements under the El-Centro earthquake



X - Displacement Y - Displacement Z - Displacement

(i) SSI CSB model



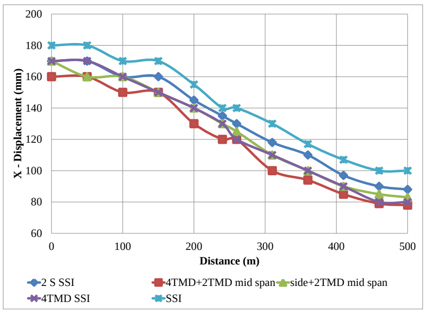
X - Displacement Y - Displacement Z - Displacement

(ii) Fixed CSB model

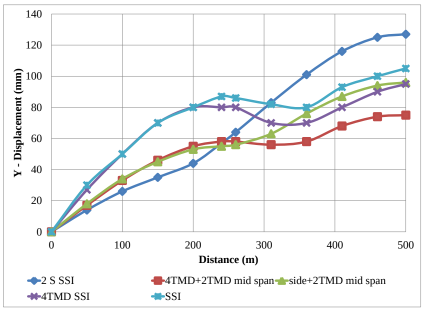
Fig. 10 Tower displacements under the El-Centro earthquake

the best arrangement of these devices on the CSB elements to give maximum mitigation efficiency. The time history analysis was used in analyzing all CSB cases.

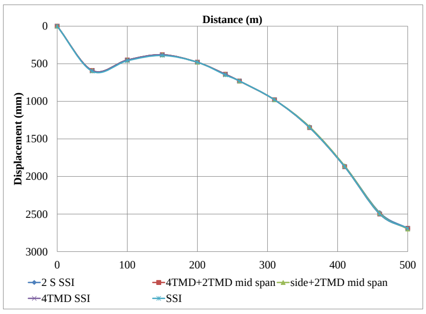
Fig. 4 shows the 3D fixed model of the CSB and Fig. 5 presents some of the eigenmodes of the fixed model of CSB. Fig. 5(i) represents the first mode of the fixed CSB with a period time equal to 13.42 sec, while in the third mode the period time decreases to 4.15 sec. Fig. 5(vi) shows the eleventh mode in which the period time is equal to 0.33 sec. Twelve (12) modes were used in this analysis.



X - Displacement

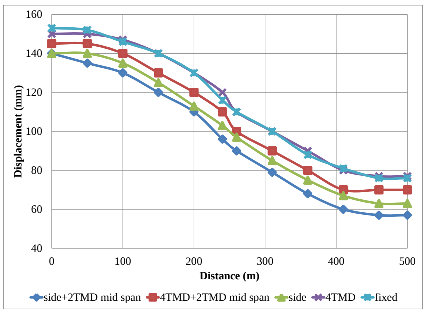


Y - Displacement

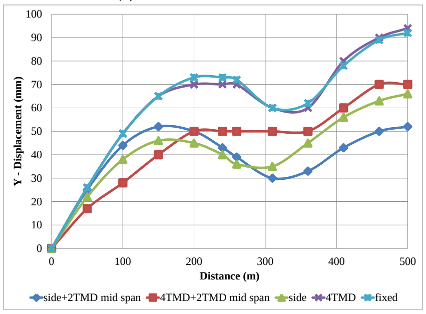


Z - Displacement

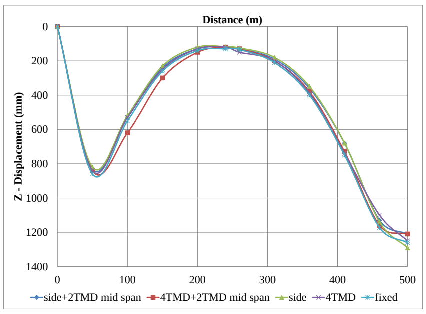
(i) SSI CSB model



X - Displacement



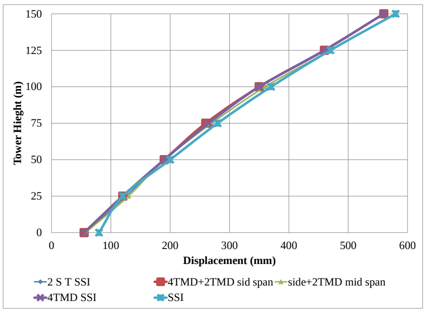
Y - Displacement



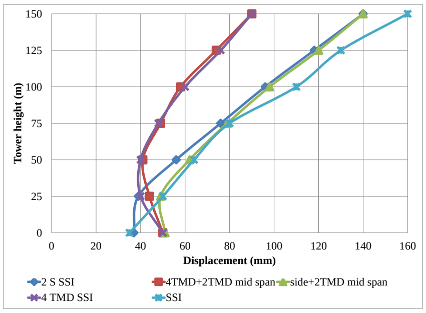
Z - Displacement

(ii) Fixed CSB model

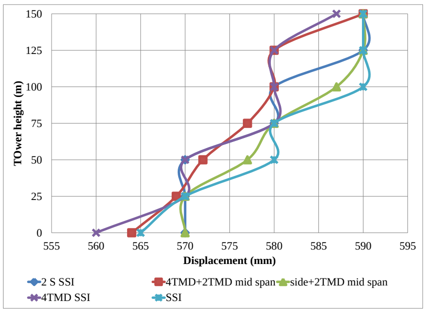
Fig. 11 Deck displacements under the Hollister earthquake



X - Displacement

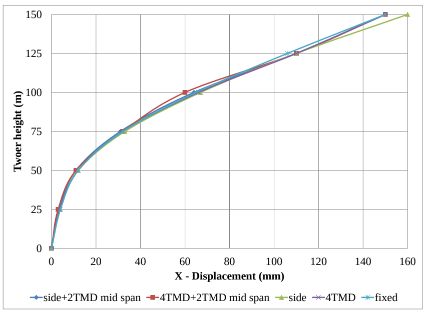


Y - Displacement

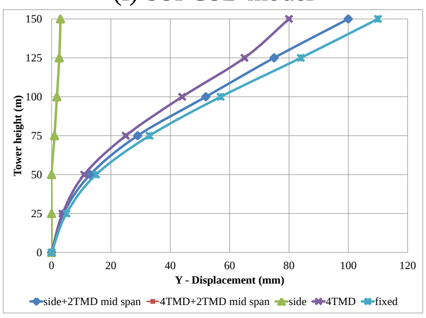


Z - Displacement

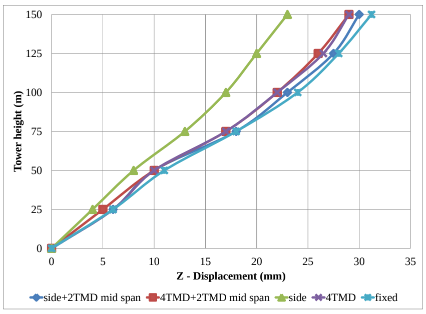
(i) SSI CSB model



X - Displacement



Y - Displacement



Z - Displacement

(ii) Fixed CSB model

Fig. 12 Tower displacements under the Hollister earthquake

Fig. 6 presents some of the eigenmodes of the model with the effect of SSI. Fig. 6(i) represents the first mode of the SSI CSB model with a period time equal to 13.16 sec (nearly equal to fixed CSB model). The third mode period is equal to 6.7 sec (more than the third mode of the fixed CSB model). Fig. 6(vi) shows the eleventh mode in which the period time is equal to 2.14 sec (more than the eleventh mode of fixed CSB model by 6.5 times).

Figs. 7 and 8 show the maximum deck and tower displacements in x, y, and z directions for different mitigation schemes compared with the non-mitigation case for the SSI and fixed CSB models subjected to the Chi-Chi earthquake.

Fig. 7(i) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different mitigation schemes taking into consideration the effect of SSI; in the x direction the largest deck displacement occurs when no mitigation schemes are used (“SSI only” case) and the lowest displacement occurs for the “4TMDs+2TMDs mid-span” scheme where this displacement decreases by nearly 2.35 times than the “SSI only” case; for the y displacement the use of “2 side dampers+2 TMDs at mid-span” decrease the displacement by 2.7 times than the “SSI only” case; finally, for vertical displacements no effect appears from the mitigation schemes.

Fig. 7(ii) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different mitigation schemes assuming fixed model; the “4 TMDs” case decreases the X-displacement by about 1.3 times than the “fixed only” case; the Y-displacement in both the “2 side dampers” and “2 side dampers+2TMDs at mid-span” schemes give the minimum displacement (less by 7 times than the “fixed only” case where no TMDs are used); the Z-displacement was not affected by the mitigation schemes.

Fig. 8(i) represents the displacements of the tower in x, y, and z directions subjected to the Chi-Chi earthquake with the effect of SSI for the CSB. The largest X-displacements are recorded in the “SSI only” (i.e., without any mitigation schemes) case and the smallest values occurred in the “4TMDs” scheme, where the “4TMDs” scheme is smaller by 1.57 times than the “SSI only” case; for the Y-displacements, the “4TMDs” and “4TMDs+2TMDs at mid-span” schemes recorded the smallest values than the other mitigation schemes (where the smallest Y-displacement values decrease by 1.7 times than the “SSI only” case; the Z-displacements recorded volatile values for all mitigation schemes but the “4TMDs” displacements decreased than the “2 side dampers+2TMDs mid-span” scheme by a small value but this is the more uniform case.

Fig. 8(ii) shows the displacements of the tower assuming fixed CSB model; the X-displacements were almost not affected by the mitigation schemes; the Y-displacements for “2 side dampers (between each tower and deck)” scheme recorded the smallest displacements values than the other cases (the fixed only case increase by 27 times than the “2 side dampers” scheme); for the Z-displacements, the “2 side dampers (between each tower and deck)” scheme recorded the smallest values than the other cases by nearly 1.39 times.

Figs. 9 and 10 show the maximum deck and tower displacements in x, y, and z directions for different mitigation schemes compared with the non-mitigation case for the SSI and fixed CSB models subjected to the El-Centro earthquake.

Fig. 9(i) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different mitigation schemes taking into consideration the effect of SSI; in the x direction the largest deck displacement occurs when no mitigation scheme is used and the lowest displacement occurs for the “4TMDs+2TMDs mid-span” scheme where this displacement decreases by nearly 1.6 times than the “SSI only” case; for the y displacement, the use of “2 side dampers+2 TMDs at mid-span” decreases the displacement by 1.56 times than the “SSI only” case, also the “2 side dampers+2 TMDs at mid-span” scheme decreases the displacement by the same values for mid-span portion (250 m to 500 m); finally, for the z displacements no effect appears from the mitigation schemes.

Fig. 9(ii) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different mitigation schemes assuming fixed model case; the use of “4 TMDs” scheme decreases the X-displacement by 1.35 times than the “fixed only” case; in the Y-displacement both the “2 side dampers” and “2 side dampers + 2TMDs at mid-span” schemes give the minimum displacement (less by 1.86 times than the “fixed only” case); the Z-displacement was almost not affected by the mitigation schemes.

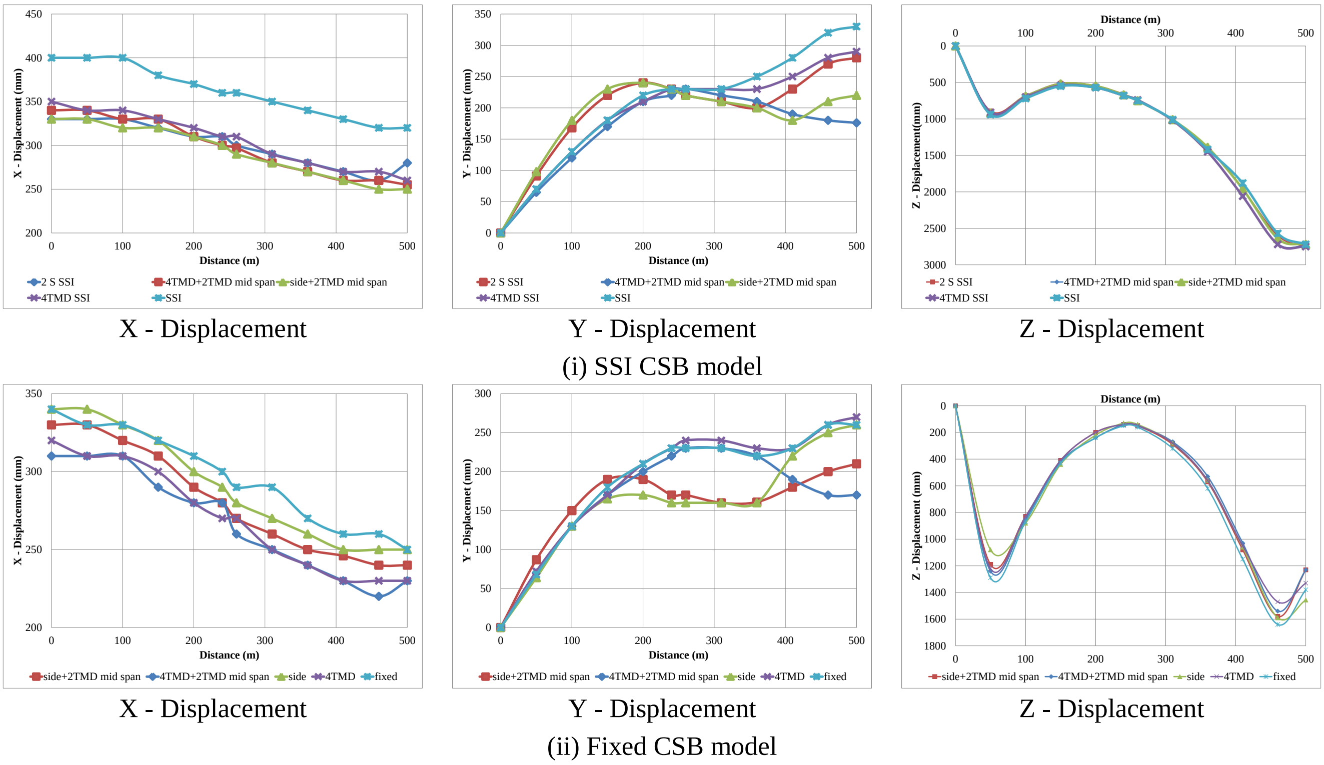
Fig. 10(i) represents the displacements of the tower in x, y, and z directions subjected to the El-Centro earthquake with the effect of SSI for CSB. The largest X-displacements are recorded in the “SSI only” case (without any mitigation schemes) and the smallest values occurred when the mitigation schemes are used (all schemes are close, the mitigation schemes are smaller nearly by 1.2 times than the “SSI only” case); for the Y-displacements, the “4TMDs” and the “4TMDs+2TMDs” at mid-span recorded the smallest values than the other mitigation schemes, where these smallest displacement values are decreased by 2 times than the “SSI only” case; for the Z-displacements the “4TMDs” and the “4TMDs+2TMDs” at mid-span recorded the smallest values than the other mitigation schemes.

Fig. 10(ii) shows the displacements of the tower assuming fixed CSB model; the X-displacement decreases by 1.67 times than the “fixed only” case when “4TMDs” at towers are used; the Y-displacement for the “2 side dampers” (between each tower and deck) recorded the smallest displacement values than the other cases (the “fixed only” case increases by 44 times than the “2 side dampers” scheme); for the Z-displacements, the “2 side dampers” (between the deck and each tower) recorded the smallest values than the other cases by nearly 1.7 times.

Figs. 11 and 12 show the maximum deck and tower displacements in x, y, and z directions for different mitigation schemes compared with the non-mitigation case for the SSI and fixed CSB models subjected to the Hollister earthquake.

Fig. 11(i) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different mitigation schemes taking into consideration the effect of SSI; in x direction the largest displacement occurs when no mitigation schemes are used and the lowest displacement for “4TMDs+2 TMDs at mid-span” which is decreased by nearly 1.25 times than the “SSI only” case; for the Y-displacement, the use of “2 side dampers and 2 TMDs at mid-span” decrease the displacement by 1.25 times than the “SSI only” case, also the “2 side dampers” increase the displacement by 1.5 times than the side dampers and 2TMDs at mid-span scheme; for the vertical displacements no effect appears from mitigation schemes.

Fig. 11(ii) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different



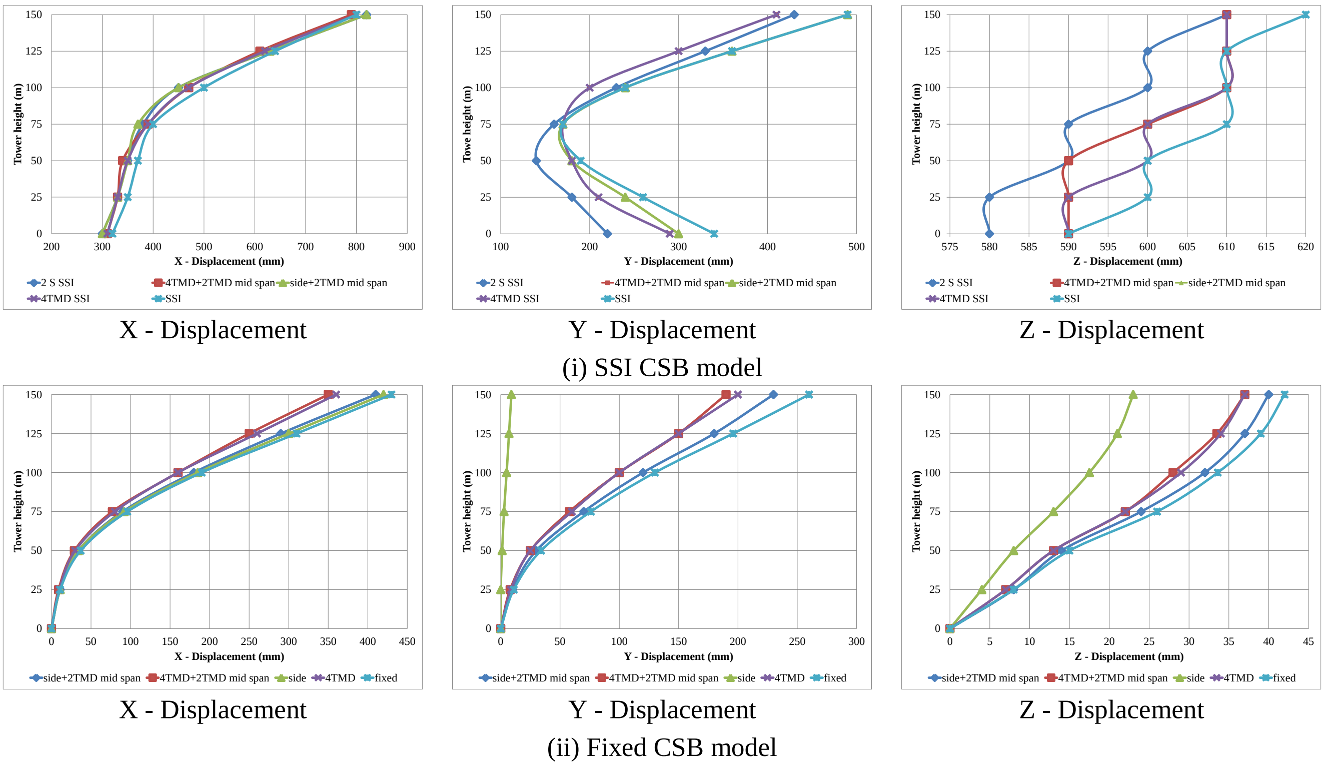
X - Displacement Y - Displacement Z - Displacement

(i) SSI CSB model

X - Displacement Y - Displacement Z - Displacement

(ii) Fixed CSB model

Fig. 13 Deck displacements under the Loma Prieta earthquake



X - Displacement Y - Displacement Z - Displacement

(i) SSI CSB model

X - Displacement Y - Displacement Z - Displacement

(ii) Fixed CSB model

Fig. 14 Tower displacements under the Loma Prieta earthquake

displacements in the "2 side dampers and 2TMDs mid-span" are decreased by 1.3 times than the "fixed only" case and the "4TMDs" scheme; the Y-displacement in both the "4TMDs" scheme and the "fixed only" cases are increased by 1.8 times than "2 side dampers and 2TMDs at mid-span" scheme; the Z-displacement is almost not affected by the mitigation schemes.

Fig. 12(i) represents the displacements of the tower in x, y, and z directions subjected to the Hollister earthquake with the effect of SSI for CSB. The X-displacement values are close for all cases; the Y-displacements in the “4TMDs” and “4TMDs with 2TMDs at mid-span” schemes recorded the smallest values than the other mitigation schemes (the smallest displacement values is decreased by 1.77 times than the “SSI only” case); for the Z-displacements the “4TMDs+2TMDs” at mid-span recorded the smallest values than the other mitigation schemes.

Fig. 12(ii) shows the displacements of the tower assuming fixed CSB model; the X-displacement values are close for all mitigation schemes and the “fixed only” case; the Y-displacements for the “2 side dampers (between each tower and deck)” scheme recorded the smallest displacement values than the other scheme, and in the “fixed only” case are increased by 22 times than the “2 side dampers” scheme; for the Z-displacements the “2 side dampers (between deck and each tower)” scheme recorded the smallest values than the other cases by nearly 1.45 times, but all mitigation schemes are close to the “fixed only” case.

Figs. 13 and 14 show the maximum deck and tower displacements in x, y, and z directions for different mitigation schemes compared with the non-mitigation case for the SSI and fixed CSB models subjected to the Loma Prieta earthquake.

Fig. 13(i) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different mitigation schemes taking into consideration the effect of SSI; in X-direction the largest displacements occur when no mitigation schemes are used (i.e., in the “SSI only” case) and the lowest displacements in the used mitigation schemes, where all displacement values are close; for the Y-displacement, the use of “4TMDs and 2 TMD at mid-span” decrease the displacement by 1.85 times than the “SSI only” case; for the vertical displacements no effect appears from the mitigation schemes.

Fig. 13(ii) shows the displacements of the deck (distance until mid-span) in x, y and z directions for different mitigation schemes assuming fixed CSB model; the X-displacement values are close for all mitigation schemes and the “fixed only” case; for the Y-displacement the most mitigation schemes decrease the displacement and especially the “2 side dampers and 2 TMDs at mid-span” scheme decreases the displacements by nearly 1.25 times than the “fixed only” case; the Z-displacement is almost not affected by the mitigation schemes.

Fig. 14(i) represents the displacements of the tower in x, y, and z directions subjected to the Loma Prieta earthquake with the effect of SSI for CSB; the X-displacement values are close for all cases; the Y-displacement values are also relatively close for all cases; for the Z-displacements the “2 side dampers (between each tower and deck)” scheme recorded the smallest displacement values than the other cases.

Fig. 14(ii) shows the displacements of the tower for the fixed CSB model; the X-displacement values are close for all mitigation schemes and the “fixed only” case; the Y-displacement for the “2 side dampers (between each tower and deck)” scheme recorded the smallest displacement values than the other cases, and the “fixed only” case is increased by 25 times than the “2 side dampers” scheme; for the Z-displacements the “2 side dampers (between each tower and deck)” scheme recorded the smallest values than the other mitigation schemes by nearly 1.82 times, but all other mitigation schemes are close to the “fixed only” case.

Fig. 15 shows the effect of using different mitigation schemes on the maximum straining actions (internal forces) in the towers of the CSB in the taking into consideration SSI case and in the fixed base CSB model.

Fig. 15(i) represents the internal forces acting on the tower with SSI effect; the “4TMDs” scheme records the lowest axial force, where no significant change in the values of the x-shear forces is observed, the “4TMDs” and “4TMDs+2TMDs at mid-span” record a decrease in the y-shear force by 1.2 times than the other cases, for the x and y moments on tower the mitigation schemes give no obvious behavior, and finally for torsion all mitigation schemes increase the values of torsion on the tower more than the no mitigation case (“SSI only” case).

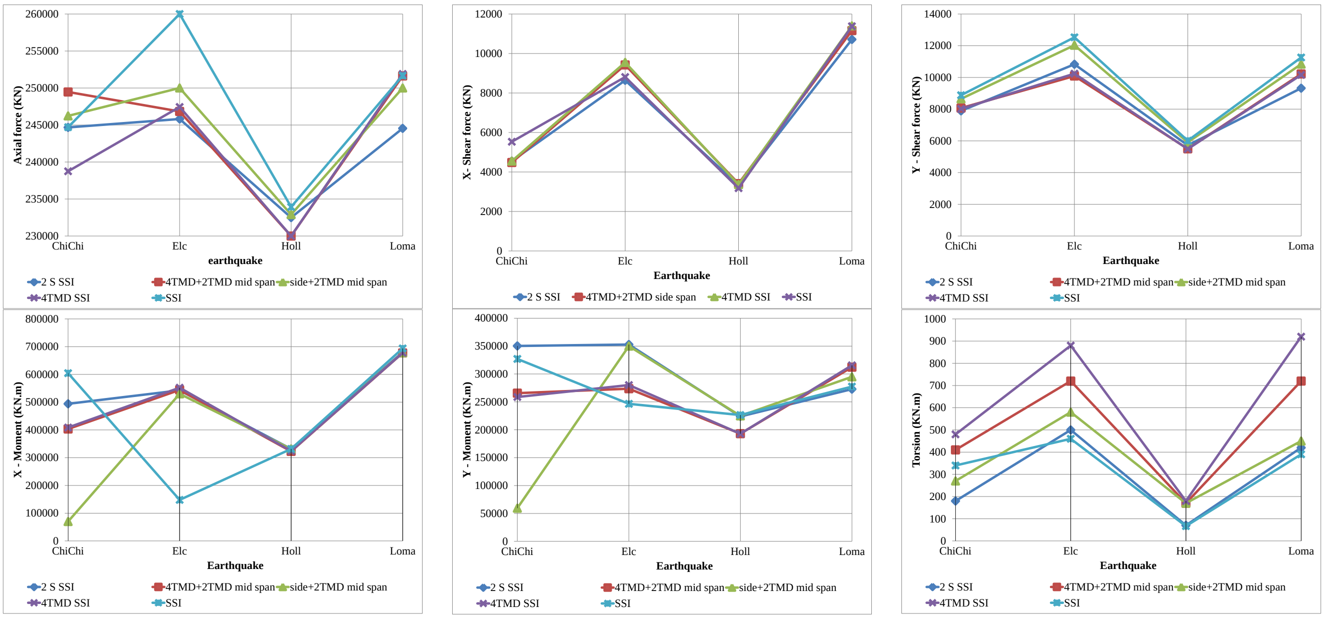
Fig. 15(ii) represents the internal forces acting on the tower for the fixed CSB model; the “2 side dampers” scheme records the lowest axial force (i.e., decrease of the axial force by 1.45 times than the other cases), no significant change in the values of x-shear forces is observed, the “2 side dampers” scheme records a decrease in the y-shear by 17 times than the other cases, for the x moments on tower the mitigation schemes give no obvious behavior, but the “2 side dampers” scheme reduces the y-moments by 23 times than the other cases, finally for torsion the “4TMDs+2TMDs at mid-span” scheme decrease the torsion by 3.2 times than the “fixed only” case but the “2 side dampers” case increase the torsion by 1.45 times than the “fixed only” case.

Fig. 16 shows the maximum tension force in the cables for the four different mitigation schemes, with and without the SSI effect; for the fixed case, the “2 side dampers+2 TMDs at mid-span” scheme records the almost lowest tension force in the cables than the other mitigation schemes. The tension force in cables decreases by using the presented four different mitigation schemes both in the fixed CSB model and the SSI CSB model.

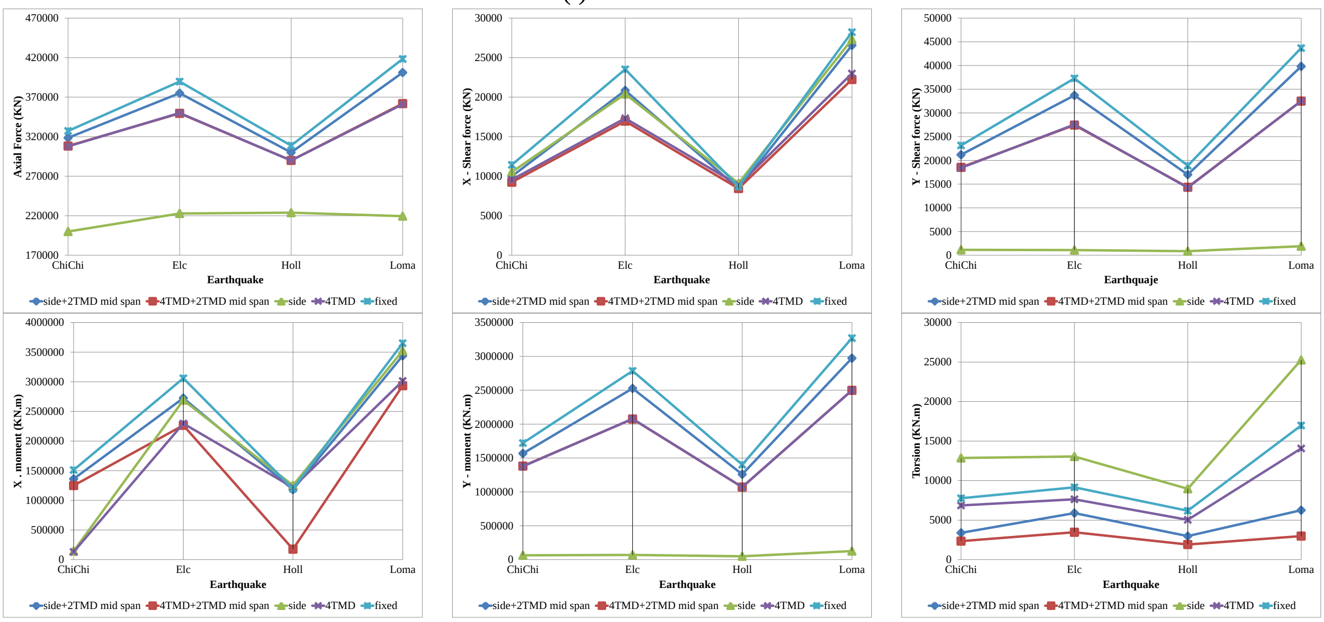
6. Conclusions

A cable-stayed bridge (CSB) is one of the most complicated structures, especially when subjected to earthquakes and taking into consideration the effect of SSI. When a CSB is subjected to an earthquake, the parts of the CSB mostly affected by the earthquake are the pylons (towers), the pylon-deck connections and the mid-span of the deck. To mitigate the harmful effect of the vibration generated from earthquakes, four different mitigation schemes were used and compared with the non-mitigation model to determine the effectiveness of each scheme, when applying on the SSI or fixed CSB models. From the presented results, the following conclusions can be drawn:

• The following three mitigation schemes were shown to be more effective: the “4TMDs+2TMDs at mid-span” scheme (i.e., 2 TMDs at the top of each pylon and 2 TMDs at the deck mid-span, one at each side of the deck), the “2

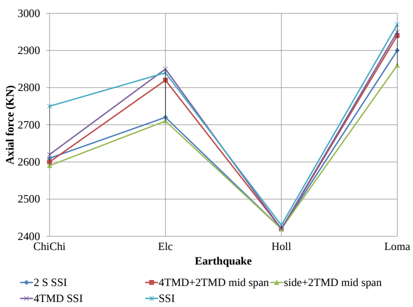


(i) SSI CSB model

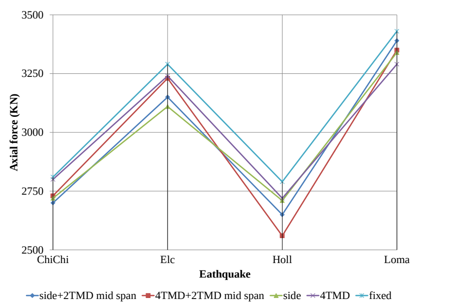


(ii) Fixed CSB model

Fig. 15 Internal forces acting on the tower



(i) Tension in cables with SSI effect



(ii) Tension in cables in the fixed CSB model

Fig. 16 Tension force in cables

side dampers+2 TMDs at mid-span" scheme (i.e., 2 side spring dampers for each pylon located at the connection of each pylon with the deck and 2 TMDs at the mid-span of the deck) and the "2 side dampers" (at the connection of each pylon with the deck) scheme.

• The x and y displacements of the deck are reduced by the mitigation schemes.

• The x and y displacements of the towers are reduced by the mitigation schemes.

• The deck vertical displacements are almost not affected by the mitigation schemes.

• The tower vertical displacements are reduced by the mitigation schemes.

• The mitigation schemes in the fixed CSB model and especially the "2 side dampers" scheme show a good efficiency in decreasing the most internal forces in towers subjected to earthquakes.

• The tension force in cables decreases by using the mitigation schemes both in the fixed CSB model and the SSI CSB model.

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