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Dynamic Analysis of Suspension Footbridges under Human-induced Vibrations and Near-field Earthquakes–Soti Ghat Bridge in Nepal

B. Samadi, G. Zamani Ahari*

Department of Civil Engineering, Faculty of Engineering, Urmia University, Urmia, Iran.

ABSTRACT: Suspension footbridges are mainly under the influence of pedestrians' loads. In addition to the forces caused by pedestrians during the structure's lifetime, natural forces such as wind and earthquake also affect these structures. The effects of wind force on the suspension bridges are generally considered in the design process of the structure due to the high repetition of this phenomenon and lightweight of these structures but the earthquake forces are ignored due to the low probability of occurrence, low mass, and the high flexibility of these structures. This study aimed to investigate the dynamic behavior of suspension footbridges under the influence of the coincidence of pedestrians loading and earthquake forces. The final finding of this study was the impact of the earthquake on the suspension footbridges, which caused a change in the acceleration and forces of the bridge cables. It was found out that the simultaneity of human loading and earthquake forces increases the response of the lateral acceleration of the structure, and this increase is affected by the acceleration of earthquakes. Moreover, the lateral acceleration response of the structure changes during the pedestrians' movement, like the vertical acceleration response, but its amount is small at different speeds and does not cause any difficulty in operating the structure.

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1- Introduction

All human-made structures, in addition to the forces applied to them during construction and operation, will be affected by natural forces during their lifetime. The most important natural phenomena that can affect the suspension footbridges include wind and earthquakes. The wind load can affect the structure and threaten it [1] due to the high probability of occurrence during the lifetime of the structure; especially these structures are usually in the direction of the wind. Hence, this phenomenon has always been considered in the design and construction of such structures. However due to the low probability of occurrence and the fact that these structures are lightweight and highly flexible, the effect of the earthquake on them is considered as low and is usually not considered. In this study, the effect of the earthquake on suspension footbridges and the effect of earthquake simultaneity with human-induced vibrations has been investigated.

2- Analytical model

As a case study, the Soti Ghat Bridge [2] – a suspension footbridge in Nepal – was chosen. The side view and the main dimensions are shown in Fig.1. The width of the deck is 2 meters and the distance between the hangers is 1.25 meters. The distance between the transverse beams - which are x-braced - is 1.25 meters. The tube section is used for all longitudinal beams, transverse beams, braces, and towers. The cross-section diameter of the transverse beams and braces is 15 cm and of the longitudinal beams is 30 cm. The main cables' diameter is 12 cm and the diameter of the hangers is 2.6 cm. The transverse beams, braces, and longitudinal beams are pin-connected to the towers. The Young's modulus is $2\times10^{11}\ N/m^2$ and the steel density is $7850\ Kg/m^3$. For the main cables and hangers, the following values were used: $F_y = 1.18\times10^{9}\ N/m^2$, $F_u = 1.57\times10^{9}\ N/m^2$, where F_y and F_u are yield strength and ultimate tensile strength, respectively. Modeling and structural analysis are done numerically using the finite element software SAP2000 [3].

3- Pedestrian load model

The pedestrian load can be considered as static or dynamic loads. In current technical codes, the static force on suspension footbridges is considered as a surface load which is a function of the weight of individuals and their probability of dispersal and consequently cannot simulate the real effects of the pedestrian movement. However, using the dynamic loading model, in addition to the weight of individuals, the effect of human movements and activities can be modeled. In the current study, the dynamic loading model has been selected for pedestrian movement.

*Corresponding author's email: g.zamani@urmia.ac.ir

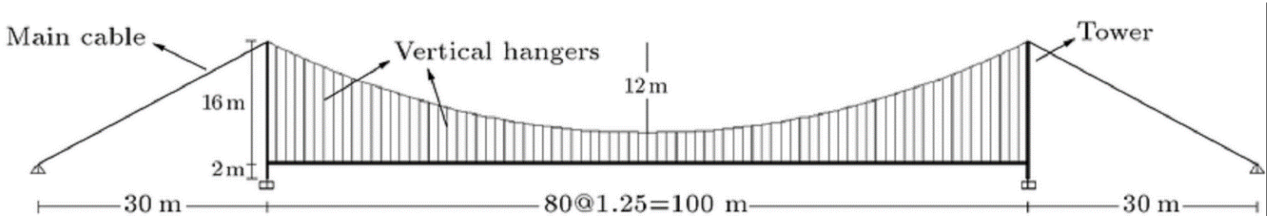

Fig. 1. Side view of Soti Ghat Bridge.

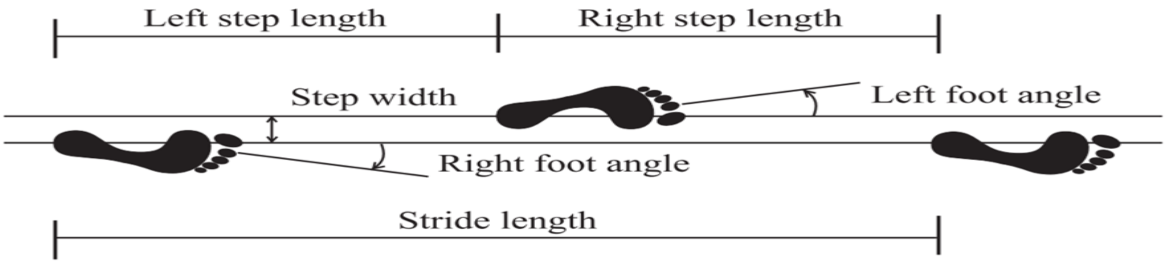

Fig. 2. Spatial parameters of walking [5].

3.1. Continuous motion

Continuous motion can be modeled using the Fourier series of Eq. (1) [4].

$$F_P(t) = G + \sum_{i=1}^{n} G\,\alpha_i\, Sin\left(2\pi\, i\, f_P\, t - \varnothing_i\right) \qquad (1)$$

where G is the pedestrian's static weight (N), i the order number of the harmonic, n the total number of contributing harmonics, α_i the Fourier coefficient of the ith harmonic generally known as dynamic loading factor (DLF), f_P the activity rate (Hz) and $\varnothing_i$ the phase shift of the ith harmonic (rad). In the existing literature, G = 700 N is commonly considered while various DLF values are reported by researchers in their publications [4].

3.2. Discontinuous motion

In nature, each phenomenon takes place in two dimensions: time and place. In fact, each action starts at a certain time and ends at another time. It must also take place in a given location, and since then the location has three components it will be a spatial dimension. Human walking is also defined at a certain time and a certain distance. The spatial parameters typically measured, are stride length, step length, and step width, while the temporal parameters commonly in use are walking speed and cadence (also known as step frequency) [5]. The spatial parameters of walking are shown in Fig.2 as a schematic diagram.

Each time the human foot reaches the bridge deck, it creates contact forces between the feet and the deck surface, which is referred to as "Ground Reaction Force" (GRF) [5]. Many attempts have been made by researchers to measure these forces to generate loading patterns for various human activities. An example of these patterns is shown in Fig. 3 and Fig.4. In fact, human motion can be considered as continuous at slow speeds and creates harmonic forces, and to simplify the model, it can be transformed into sinusoidal pulses, as shown in Eq. (2) [6]. Therefore, the patterns shown in Fig.3 are converted to the sinusoidal pulses of Fig.5.

$$f(t) = \begin{cases} K_P\, P\, Sin\left(\pi f_P\, t\right) & t < t_P \\ 0 & t_P < t < T_P \end{cases} \qquad (1)$$

where t_P represents the human step duration, T_P is the step period defined by the relationship $1/f_P$ and the variable K_P is defined by the ratio $F(t)_{max}/P$. In this expression, $F(t)_{max}$ is the maximum amplitude of the sinusoidal function and P is the individual weight, as presented in Fig.5 [6].

3.3. Idealization of vertical force patterns

In the current study, the pedestrian motions are modeled as discontinuous using the idealization of vertical force patterns derived from the experimental research works. In fact, the pattern of forces shown in Fig.4 is idealized as shown in Fig.6.

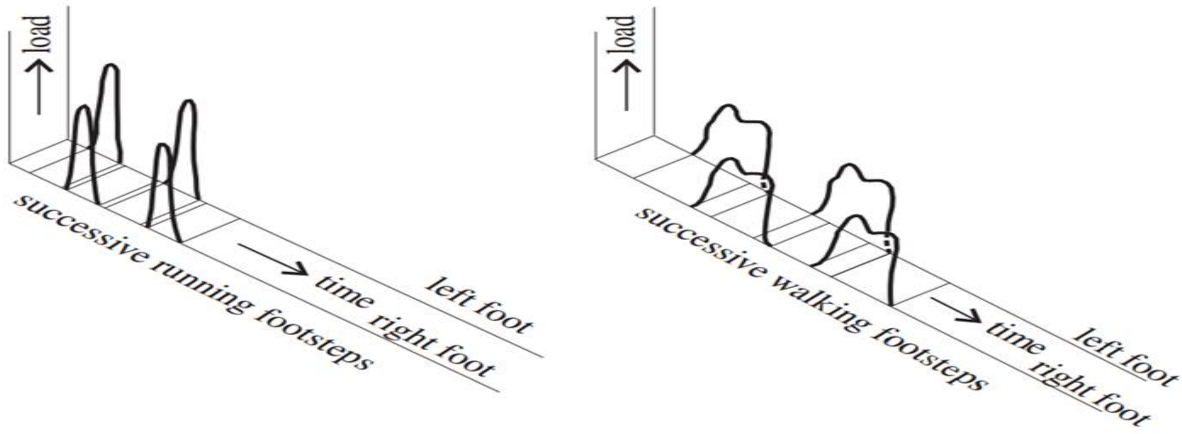

Fig. 3. 3D vertical GRF patterns for walking and running [4, 5].

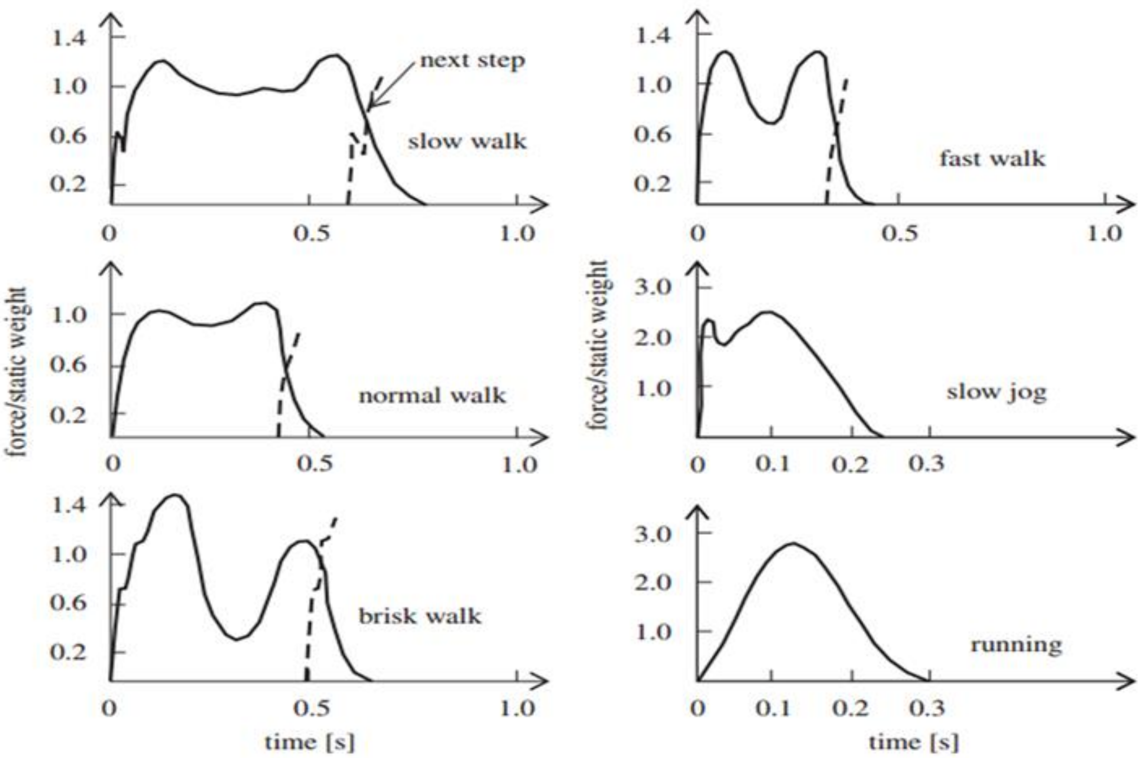

Fig. 4. Typical vertical force patterns for different types of human movements [4, 5].

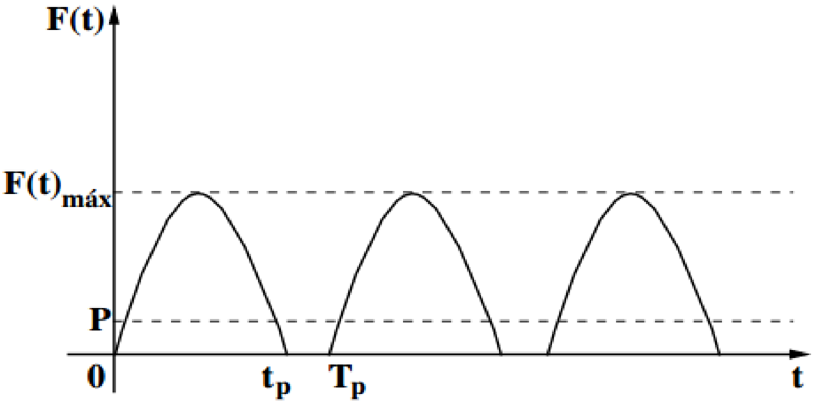

Fig. 5. Discontinuous contact dynamic excitation [6].

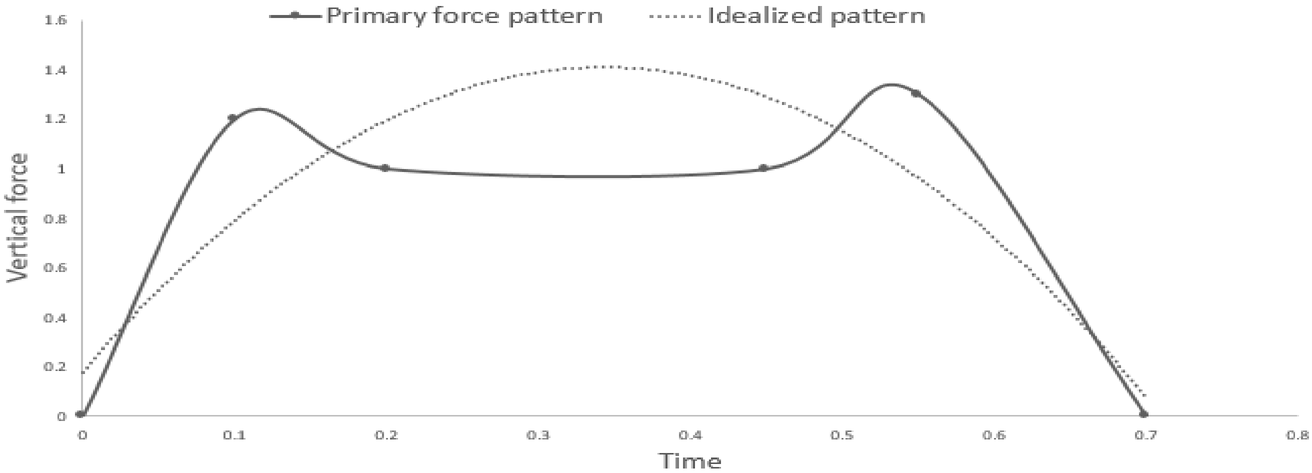

Fig. 6. Initial vertical and ideal forces for a slow walk.

Table 1. Specification of the loading models.

Model Number	*1*	*2*
Number of groups	*30*	*30*
Total number of people	*60*	*60*
Walk type	*Slow walk*	*Normal walk*
Walking speed (m/s)	*1.25*	*1.5*

3.4. Information of loading model

The loading model in this study is the synchronized motion of dual-pedestrian groups moving at two different speeds. The information about the number of people moving and the speed of the motion is presented in Table 1.

4- Applied earthquake records

In this study, the earthquake accelerations were applied to the structures at the foundations of the bridge main cable in both horizontal and vertical directions. The earthquake actions were applied to the structure in two modes, as for the first one, the pedestrians' load was not considered, while in the latter mode, the effect of the coincidence of the earthquake and passing pedestrians were analyzed. To investigate the structural behavior under an earthquake, the record of three earthquakes was used. The characteristics of these earthquakes are listed in Table 2.

Table 2. Selected earthquake records for analysis [7].

Record	Ms	d (km)	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)
Loma Prieta, USA, 1989, Gilroy Array	6.93	8.84	407.1	33.6	8.02
Kobe, Japan, 1995, Kobe University	6.9	0.9	270.8	55.3	15.16
San Fernando, USA, 1971, Lake Hughes	6.61	22.23	148.1	18.16	3.12

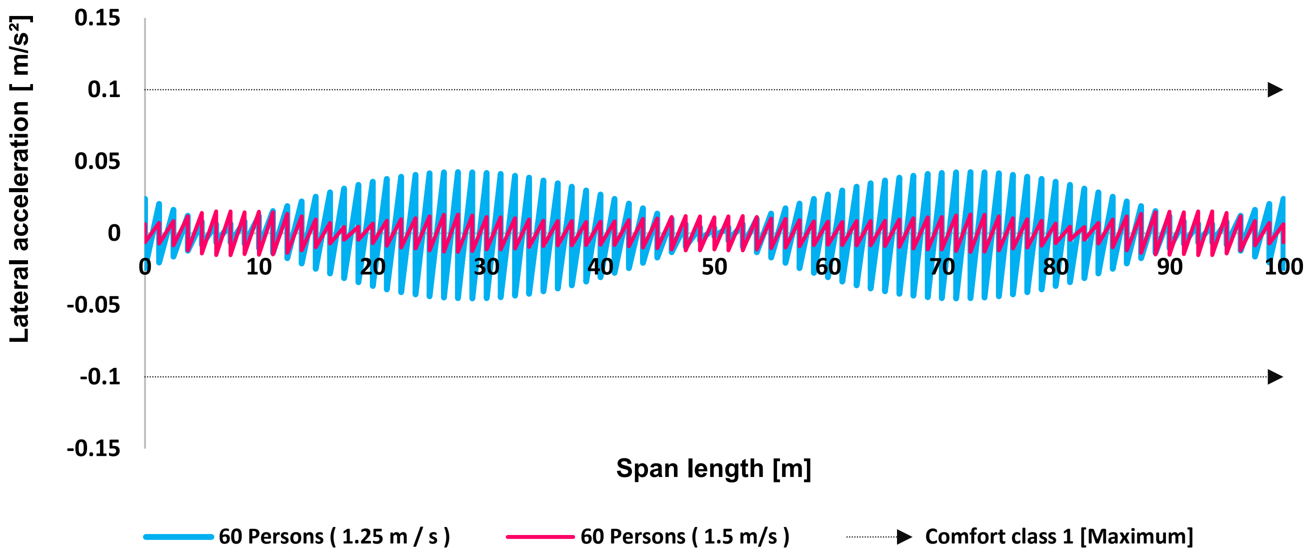

Fig. 7. The lateral acceleration response of the structure under human loading

5- Results and Discussion

5.1. Results of human loading

The results of the analysis on the Soti Ghat bridge are presented in this section. These results will include the acceleration of the suspension bridge, the main cables, and the hanger force. The acceleration comfort classes, which are presented in EUR 23984 EN code [8, 9], are used to compare the structural acceleration responses. The response of the lateral acceleration of the structure under the human loading for two speeds is shown in Fig.7. For each loading group, the lateral acceleration response of the structure is very small, so that in comparison with the EUR 23984 EN criteria for the lateral response, it provides the most comfort for pedestrians.

The vertical acceleration response is shown in Figure 8. The vertical acceleration response for the first group is slightly beyond the limit while it is mainly within the boundary ranges and the comfort class is at least minimal. Also, the vertical acceleration response for the second group of loading is beyond the minimum comfort class and so in the unacceptable range. According to Fig.8, it can be seen that the acceleration response of the structure in the first group is in the form of almost uniform pulses while for the second group, it is composed of more narrow and irregular pulses.

The main cable force under human loading is shown in Figure 9. The tensile force of the main cable for the first group is higher than the second group, due to the greater strike and duration of the strike.

The force of the hanger cables is shown in Fig.10. The amount of this force in the first group is more than the second group, but the force variation in the second group is more than the first group, as presented in Fig.10.

5.2. Results of seismic loading

In this study, the earthquake records were applied to the structure in two horizontal and vertical directions. The structure was subjected to each earthquake in two different modes; as the first mode, without the effect of human loading, and then the simultaneity of the earthquake and the human loading were considered as the second mode. The obtained results are described below.

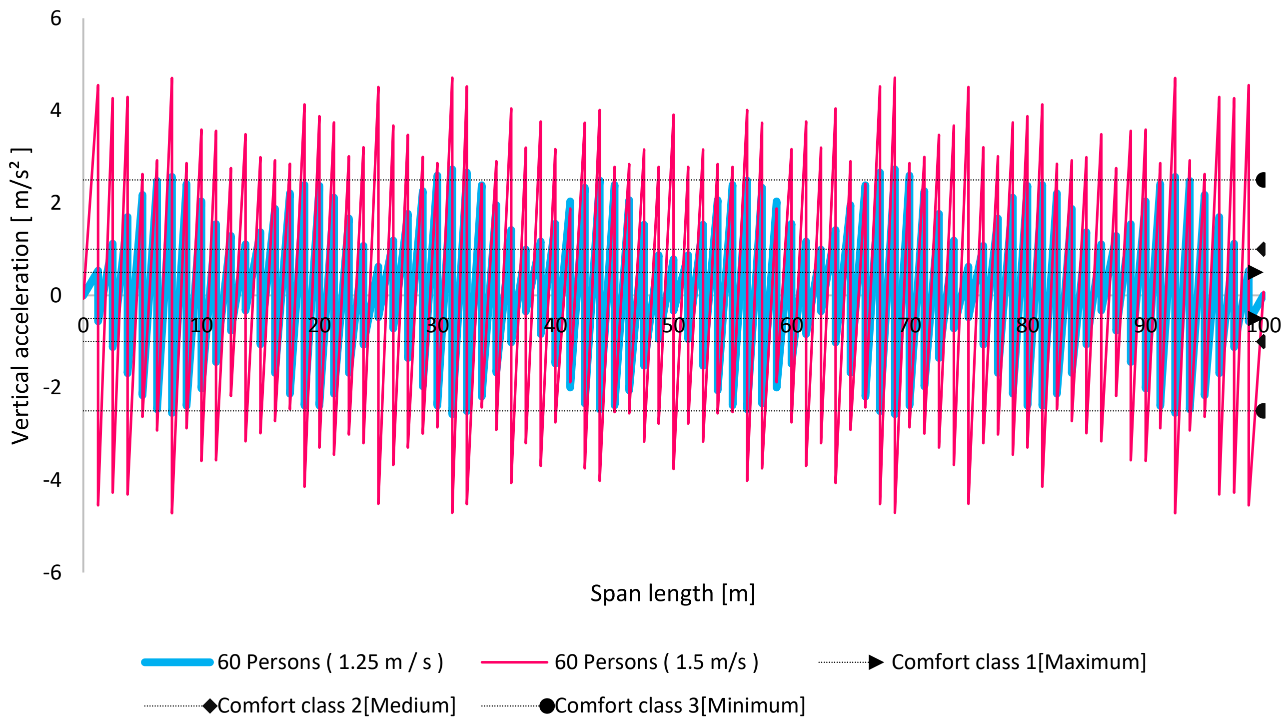

Fig. 8. The response of the vertical acceleration of the structure under human loading.

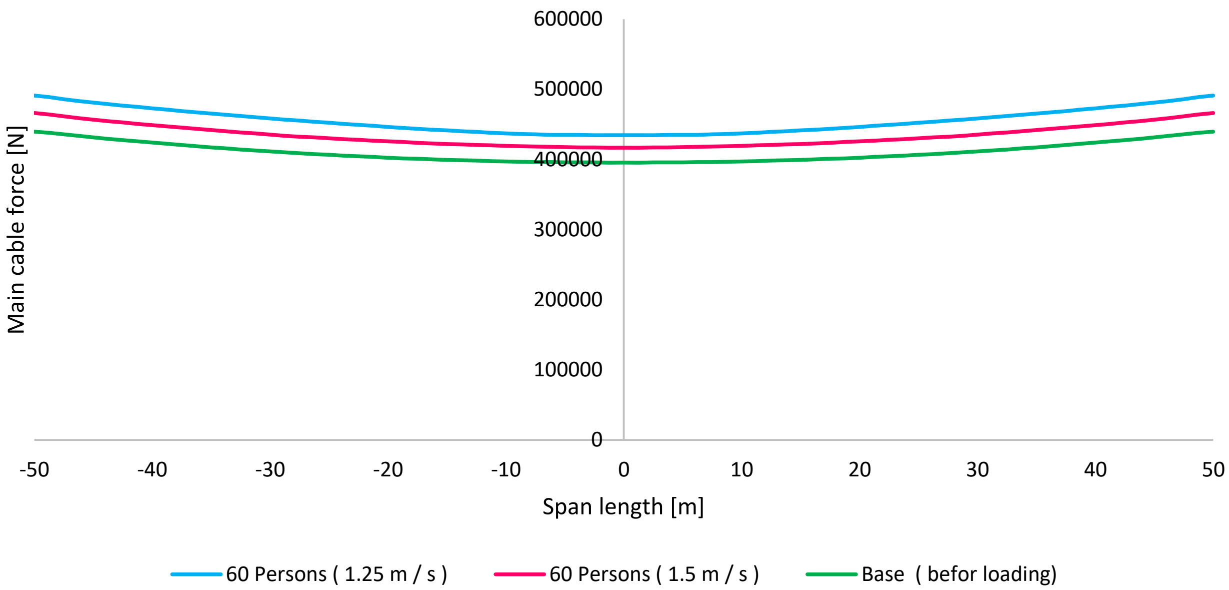

Fig. 9. The main cable force under human loading.

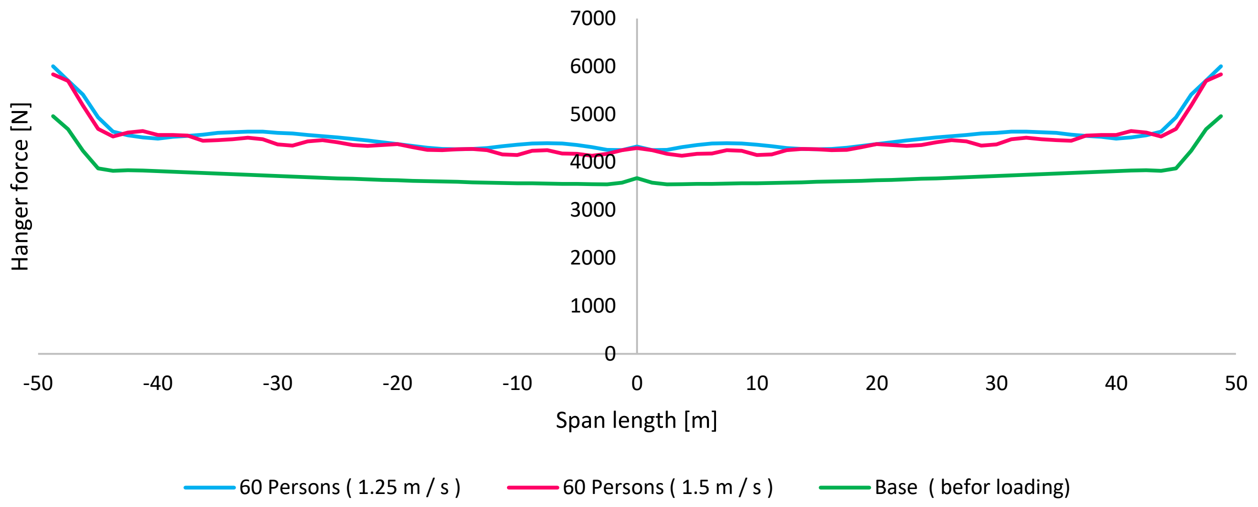

Fig. 10. The hanger cables force under human loading.

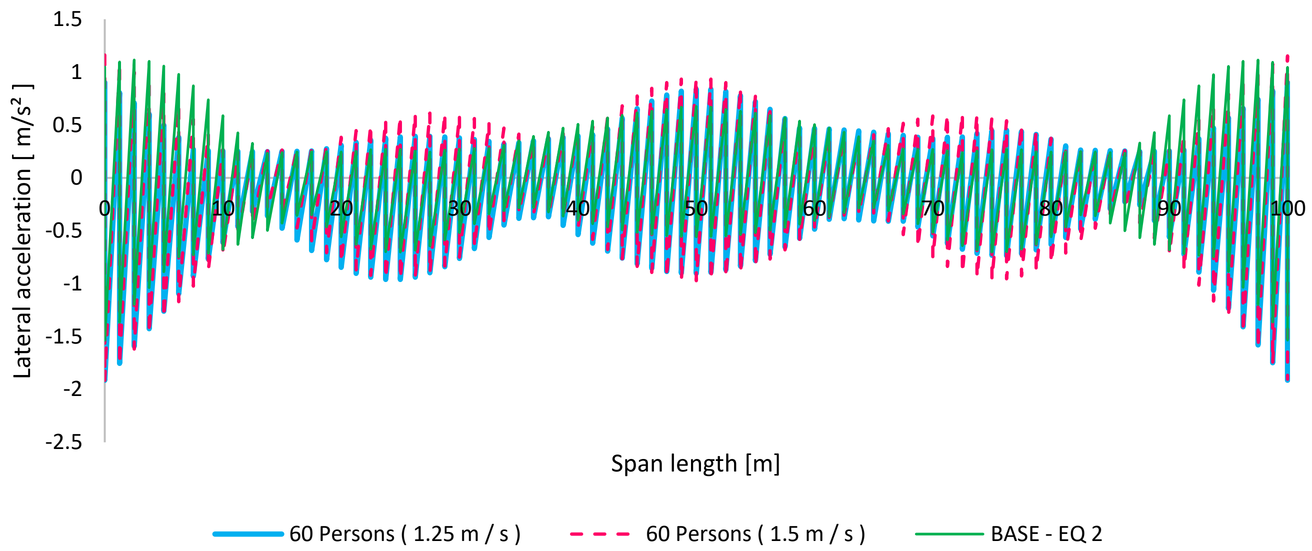

Fig. 11. The response of the lateral acceleration under the Loma Prieta earthquake.

The response of the lateral acceleration of the structure under the influence of the Loma Prieta, Kobe, and San Fernando earthquakes is shown in Fig.11, 12, and 13, respectively. Considering that the response of the lateral response shown in Figure 13, the response of the lateral acceleration under the Loma Prieta earthquake acceleration under human loading is very small and the most critical response to the lateral acceleration of the structure will be under the influence of an earthquake.

The vertical acceleration response of the structure under the influence of the Loma Prieta, Kobe, and San Fernando earthquakes is shown in Figures 14, 15, and 16, respectively. The effect of the simultaneity of the earthquake and human loading has increased the vertical acceleration response of the structure.

The tensile force of the main cables for the first group of loading under the three earthquakes is shown in Figure 17, which is the highest for the Loma Prieta, San Fernando, and Kobe earthquakes, respectively. The earthquakes increase the

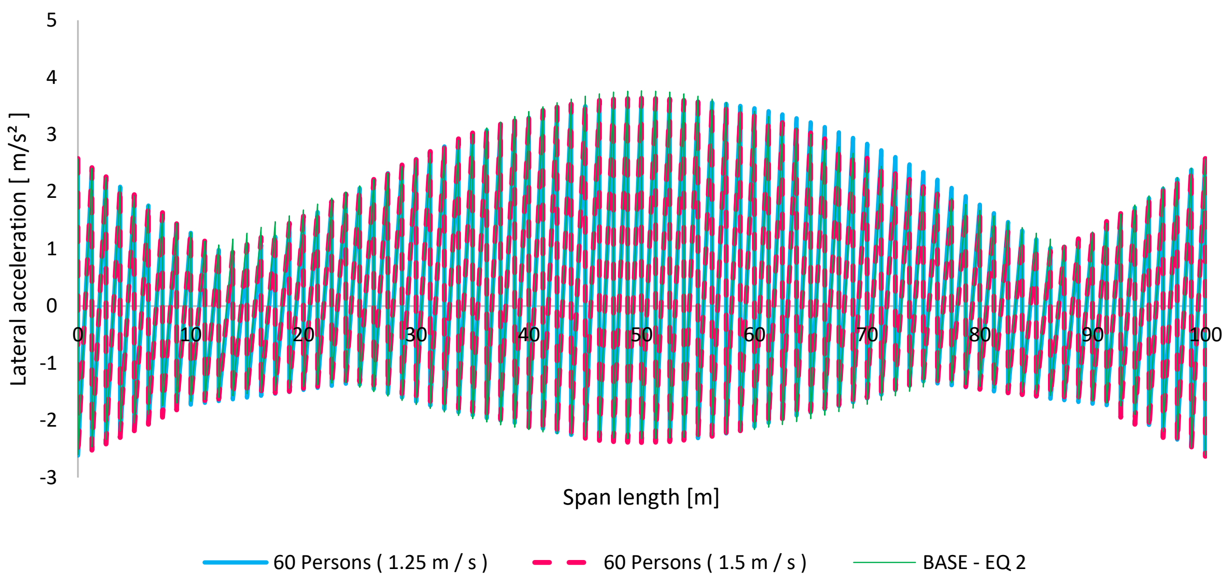

Fig. 12. The response of the lateral acceleration under the Kobe earthquake.

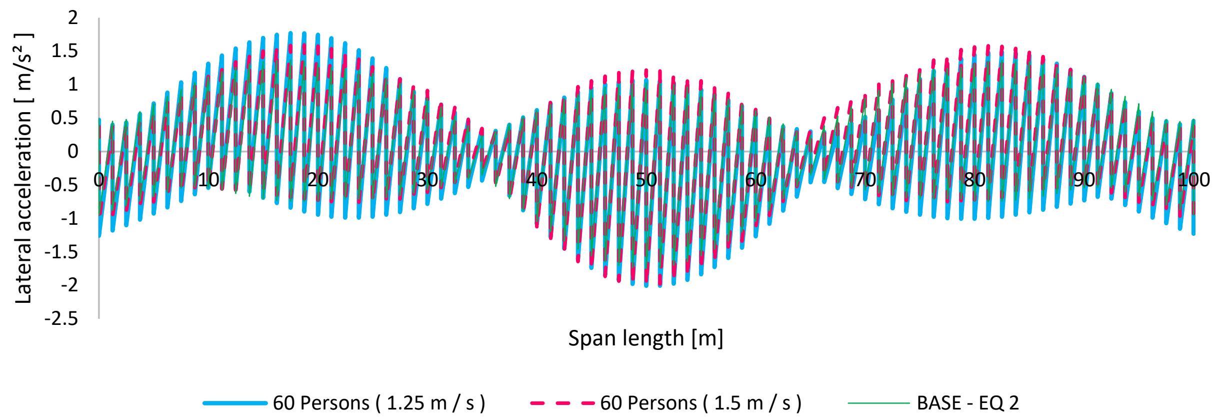

Fig. 13. The response of the lateral acceleration under the San Fernando earthquake.

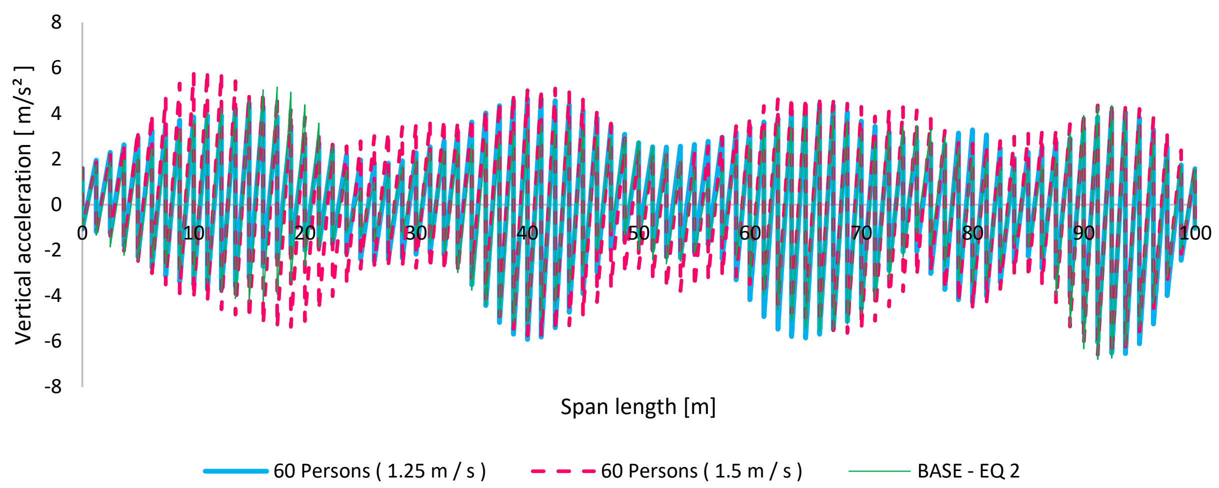

Fig. 14. The response of the vertical acceleration under the Loma Prieta earthquake.

Fig. 15. The response of the vertical acceleration under the Kobe earthquake.

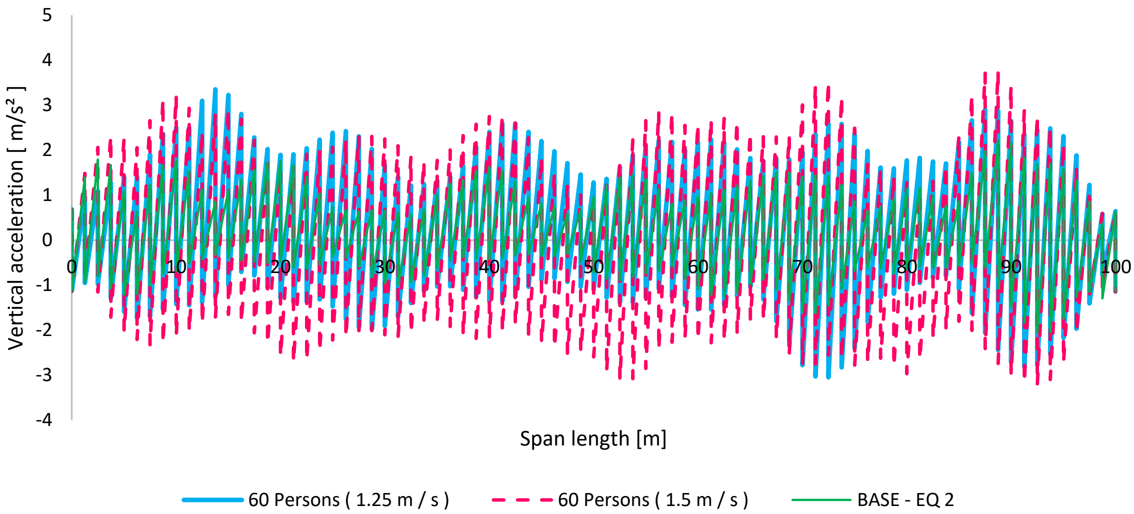

Fig. 16. The response of the vertical acceleration under the San Fernando earthquake.

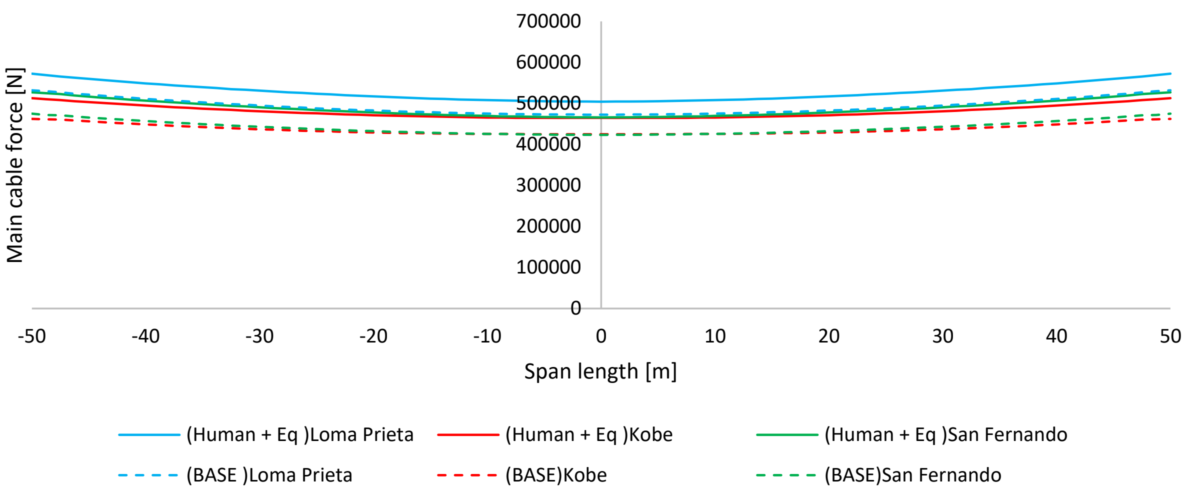

Fig. 17. Main cable force for the first loading group under the earthquake effect.

tensile force of the main cable. The tensile force variations in the main cables for pedestrian-free structures under the influence of the three earthquakes, Loma Prieta, Kobe, and San Fernando, are on average 16.77 %, 6.07 %, and 7.01 %, respectively. The tensile forces variation in the main cable taking into account the force of pedestrians and the simultaneity of the earthquake for the three Loma Prieta, Kobe, and San Fernando earthquakes are 13.28 %, 5.17 %, and 6.71 %, respectively.

The tensile force of the main cables for the second group of loading under the three earthquakes is shown in Figure18, which is the highest for the Loma Prieta, San Fernando, and Kobe earthquakes, respectively. The tensile forces variation in the main cables taking into account the force of pedestrians and the simultaneity of the earthquake is comparable to that of only pedestrians moving on for three Loma Prieta, Kobe, and San Fernando earthquakes are 13.34 %, 2.2 %, and 2.47 %, respectively.

The tensile force of the hangers for the first group of loading under the three earthquakes is shown in Figure19, which is the highest for the Loma Prieta, San Fernando, and Kobe earthquakes, respectively. The tensile force variations in the hangers for pedestrian-free structures under the influence of three earthquakes, Loma Prieta, Kobe, and San Fernando, are on average 36.39 %, 12.83 %, and 15 %, respectively. The tensile forces variation in the hangers for the structure, taking into account the force of pedestrians and the simultaneity of the earthquake, for three Loma Prieta, Kobe, and San Fernando earthquakes are 42 %, 27.9 %, and 35.2 % respectively.

The tensile force of the hangers for the second group of loading under the three earthquakes is shown in Figure 20, which is the highest for the Loma Prieta, San Fernando, and Kobe earthquakes respectively. The tensile forces variation in the hangers for the structure, taking into account the force of pedestrians and the simultaneity of the earthquake, for three Loma Prieta, Kobe, and San Fernando earthquakes are 31.1 %, 14.9 %, and 23.5 %, respectively.

6- Conclusions

- Pedestrian movement speed can affect the vertical acceleration response so that at a speed of 1.25 m/s the vertical acceleration response is in the form of regular pulses and at a speed of 1.5 m/s the vertical acceleration response is in the form of narrow pulses and irregularly is appeared.
- The response of the lateral acceleration of the structure during pedestrian crossing changes, such as the vertical acceleration response, but its amount is small at different speeds and does not cause any difficulty in operating the structure.

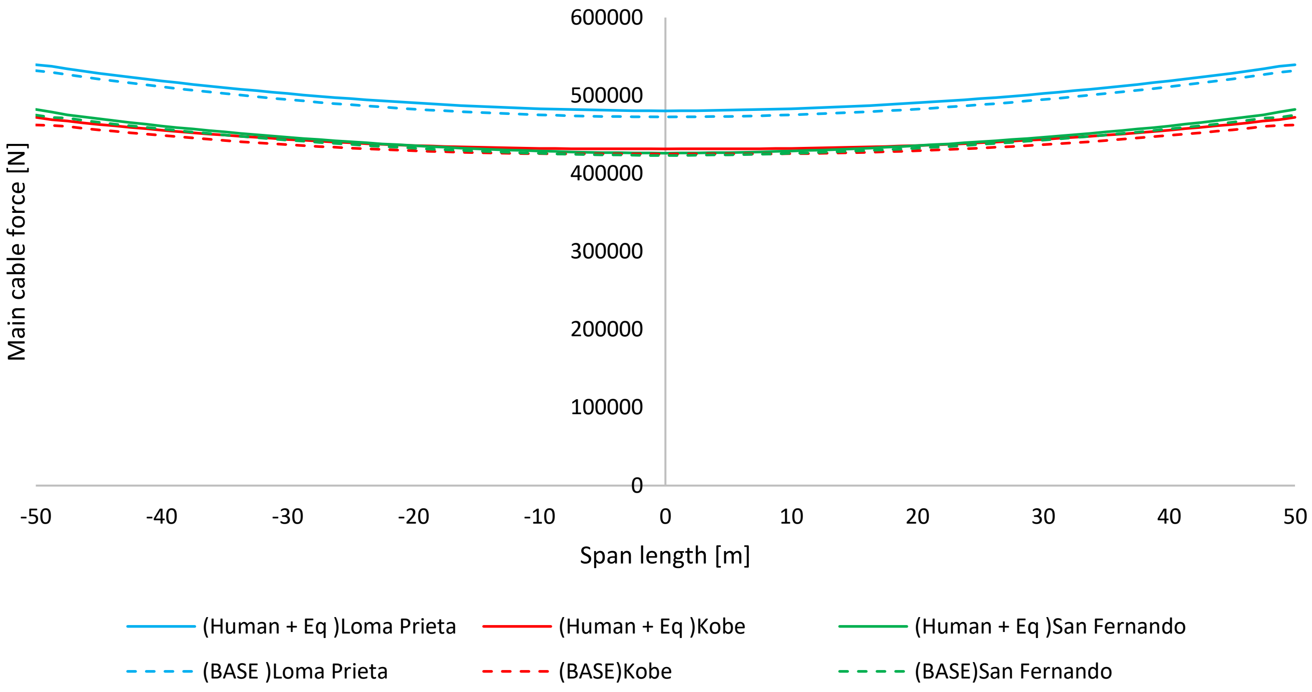

Fig. 18. The main cable force for the second loading group under the earthquake effect.

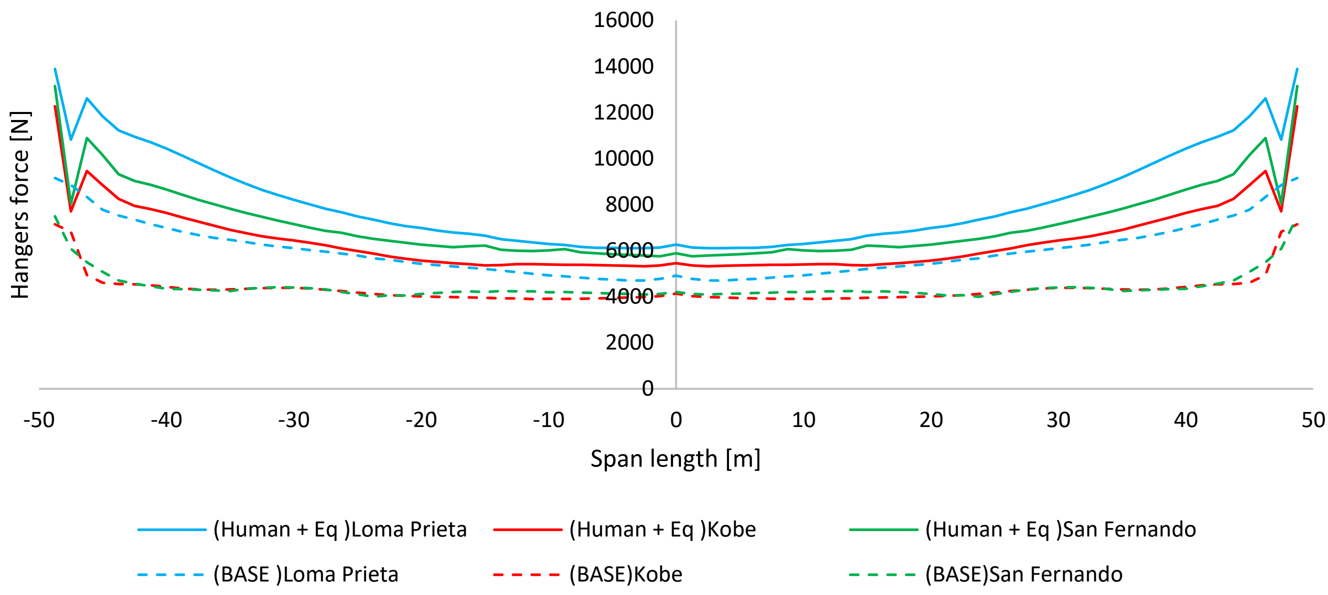

Fig. 19. Hanger's cable force for the first loading group under the earthquake effect.

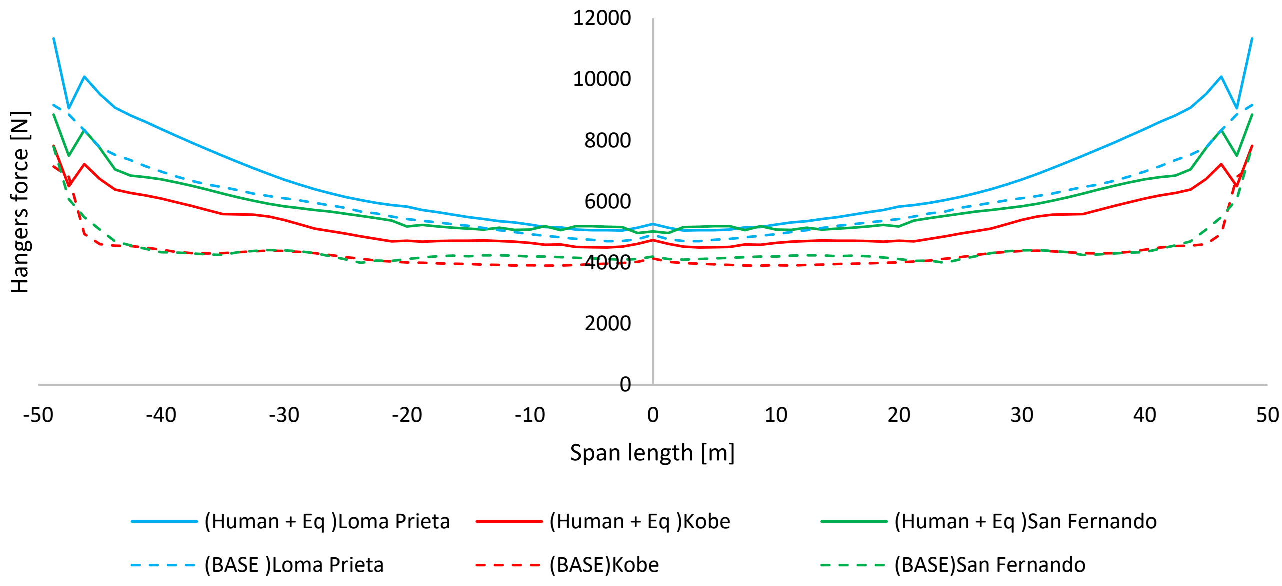

Fig. 20. The hanger cables for the second loading group under the earthquake effect.

- The simultaneity of human loading and earthquake forces increases the response of the lateral acceleration of the structure, and this increase is affected by the acceleration of the earthquake.
- The effect of simultaneity of human loading and earthquake forces on the vertical acceleration response of the structure causes a change in the overall shape and intensity of the response.
- The earthquake forces increase the tensile force of the main cable and the hangers, and this increase in tensile force for the main cables and hangers is about 10 % and 35 %, respectively.

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