INVESTIGATION OF SOME STRUCTURAL BEHAVIORS OF SUSPENSION FOOTBRIDGES WITH SOIL-STRUCTURE INTERACTION

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ABSTRACT

Structural responses in civil structures depend on various conditions. One of them which can effects on the structural behavior is the type of boundary conditions in structures. In this paper, a suspension footbridge with inclined hangers has been analyzed with two boundary conditions, once with a fixed support and another with a support relying on a soil material. Suspension footbridges can be prone structures in order to investigate soil effects on their structural responses because they consist of considerable flexibility and also geometrically nonlinear members such as main cables and hangers. In this paper, the footbridge has been modeled as two 2 dimensional finite element models with mentioned boundary conditions. These models have been analyzed statically under excessive pedestrian loads in the vertical direction and compared with respect to some structural responses. Finally a modal analysis has been carried out to compare two models. The analyses showed that the model with soil-structure interaction provides considerably different structural responses in comparison with the model without soil considering especially in the case of cable systems. Also the analysis showed that considering soil-structure interaction results changes in natural modes and decreases in frequencies of the footbridge.

Keywords: *Suspension Footbridge, Inclined Hanger, Slackness, Soil-Structure Interaction, Nonlinear Finite Element*

I. INTRODUCTION

Suspension bridges are among the structures that can be constructed over long spans, and due to the high accuracy, performance, computing and control system after implementation, they are safe to use [1, 2]. There are several physical parameters which effect on structural behavior of suspension bridges. One of them is the support condition under foundations. These structures usually be analyzed by considering a rigid support under them but in fact, there is often a kind of soil relying under the structure. Structural response is usually governed by the interplay between the characteristics of the soil, the structure and the input motion. The process, in which the response of the soil influences the motion of the structure and vice versa, is referred to as Soil-Structure Interaction (SSI). Compared with the counterpart fixed-base system, SSI has four basic effects on structural response. These effects can be summarized as: (i) increase in the natural period of the system, (ii) increase in the damping of the system, (iii) increase in displacements of the structure, and (iv) change in the base shear depending on the frequency content of the input motion and dynamic characteristics of the soil and the structure [3].
In previous researches, the performance of footbridges has usually been investigated with respect to structural parameters and the effect of soil-structure interaction usually has not been considered. Suspension bridges often represent nonlinear behaviors because of nonlinear characteristics of cables.

So it can be important to take into account the soil-foundation interaction in order to achieve more real responses in suspension bridges. Pedestrian suspension bridges usually have inclined or vertical hanger systems, which transfer forces from the deck to main cables. Inclined hangers due to the damping role against dynamic and lateral loads act better than vertical ones. But inclined hangers due to slacking under excessive tension forces and also due to early fatigue - in comparison with vertical hangers effect on structural behavior of suspension footbridges [1, 2].

The importance of SSI both for static and dynamic loads has been well established and the related literature spans at least 30 years of computational and analytical approaches to solving soil–structure interaction problems. Several researchers such as Veletsos and Meek [4], Gazetas and Mylonakis [5], Wolf and Deeks [3] and Galal and Naimi [6] studied structural behavior of un-braced structures subjected to earthquake under the influence of soil-structure interaction. Examples are given by Gazetas and Mylonakis [5] including evidence that some structures founded on soft soils are vulnerable to SSI.

Khoshnoudian et al. [7] investigated a building responses such as displacements, forces, uplift et al. using a finite element method with considering nonlinear material behavior for soil. Their studies showed the importance of uplift foundation on the seismic behavior of structures and the beneficial effects of foundation uplift in computing the earthquake response of structures are demonstrated. Two buildings have been modeled and then analyzed by Makhmalbaf et al. [8] using nonlinear static analysis method under two different conditions in nonlinear SAP2000 software. In the first condition the interaction of soil adjacent to the walls of basement is ignored while in the second case this interaction has been modeled. According to the results, soil- structure interaction has always increased the base shear of buildings, decreased the period of structure and target point displacement, and often decreased the internal forces and displacements. Boostani et al. [9] investigated the nonlinear behavior of various steel braced structures placed on different types of soil with varying hardness. This can help in better understanding of the actual behavior of structure during an earthquake. Saez et al. [10] investigated the accuracy of 2D finite element plane-strain computations compared to complete 3D finite element computations for dynamic non-linear soil-structure interaction problems. In a research, Gazetas and Apostolou [11] evaluated the response of shallow foundations subjected to strong earthquake shaking. They examined nonlinear soil–foundation effects with an elasto-plastic soil behavior. Reinforced concrete R/C stack-like structures such as chimneys are often analyzed using elastic analyses as fixed base cantilever beams ignoring the effect of soil-structure interaction. To investigate the effect of foundation flexibility on the response of structures deforming into their inelastic range, a method is presented by Halabian and Kabiri [12] to quantify the inelastic seismic response of flexible-supported R/C stack-like structures by non-linear earthquake analysis. Using a practical stack-like structure and an actual ground motion as excitation, they calculated and compared elastic and inelastic response of structure supporting on flexible soil.

In a study, two structural models comprising five and fifteen storey moment resisting building frames are selected in conjunction with three different soil deposits by Tabatabaiefar et al. [13]. These models are modeled and analyzed under two different boundary conditions namely fixed-base (no soil-structure interaction), and considering soil-structure interaction. The results indicated that the inter-storey drifts of the structural models resting on soil types increase when soil-structure interaction is considered. Also, performance levels of the structures changed from life safe to near collapse when dynamic soil-structure interaction is incorporated.

There are usually two types of nonlinearity surrounding the bridge foundation which can influence on structural behavior of cable (main cable and hangers) systems and stiffening beams (longitudinal beam of spans). These are soil nonlinear behavior and soil-foundation nonlinear behavior such as the foundation uplift. In this paper, the structural responses of a suspension footbridge have been investigated with respect to two conditions: first without considering the soil influence and second with taking into account soil influence on the superstructure. To analyze the structure with both assumptions, statically symmetric and asymmetric loads due to pedestrians have been used. A 2D finite element computation assuming plane-strain condition for the soil has been carried out in order to assess the role of non-linear soil behavior on the superstructure responses. The structural responses have been investigated for hangers especially slackness and overstress, main cable forces and stiffener beam forces and deflections. Also as an initial step of dynamic investigation, natural modes and frequencies of the bridge have been compared for both assumed models. In analyzing footbridges, it should be noted that natural frequencies of the structure are very sensitive because pedestrian dynamic loads can play an important role especially in the case of resonance vibrations.

II. Materials and Methods

2.1. Analytical Models

As a case study, the data of Soti Ghat Bridge [1, 2] - a pedestrian suspension bridge - was chosen. This Bridge has a main span of 100 meters length. The height of bridge's tower is 16 meters. Longitudinal beam (deck) is considered as a steel pipe cross section which can support dead and live loads applied on the bridge (see figure 1). The footing system of the bridge's towers is square shallow foundation type with 2 m width and 0.7 m thickness. It should be noted that anchors of main cables are assumed as fixed supports. However, this footbridge with fixed foundations is assumed as the first model in this paper. As another model with soil- structure interaction, the footbridge is assumed including the soil finite element model relying under the structure. Figure 2-a and 2-b show the second considered model including the soil model. According to figure 2-a, the distance between main cable anchor and shallow foundation is about 50 m, so the effect of main cable anchor is neglected in this research. Also it has been assumed that soil-structure interaction under shallow foundations does not depend on main cable anchors. Also the width of the soil model was found by try and error processes. It was so selected that increasing in it does not effect on soil- foundation response, so 160m width has been selected. In the case of soil's depth, 30 m amount has been considered with respect to existence of a bed rock at this elevation (see figure 2-a). For all structural members—except main cables and hangers— Young's modulus and density were considered as 2 $\times 10^{11}$ N/m^2 and 7850 kg/m^3 respectively. The hangers of the bridge are inclined cable systems. For main cables and hangers, f_y and f_u values were used as 1.18×10^9 N/m^2 and 1.57×10^9 N/m^2 and the density of 7850 kg/m^3, where f_y and f_u are yield stress and tensile strength respectively.

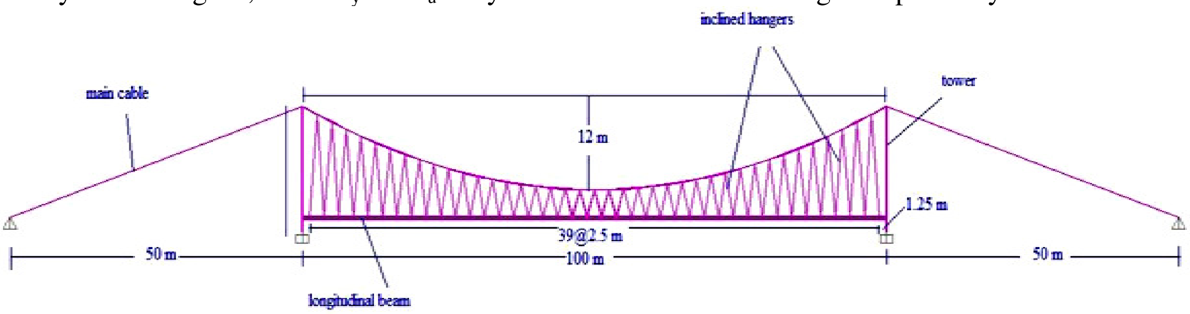


Figure 1. The suspension footbridge model with fixed foundations (model 1)

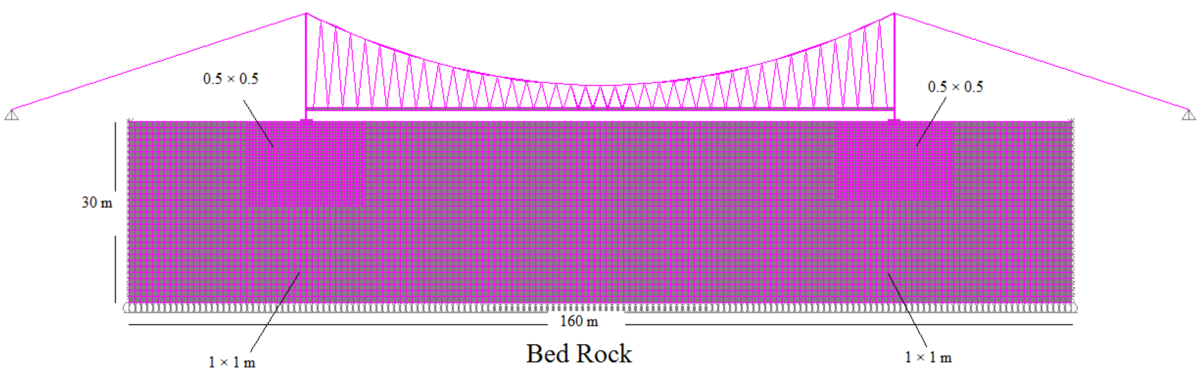


Figure 2-a. The suspension footbridge model with foundations on the soil material (model2)

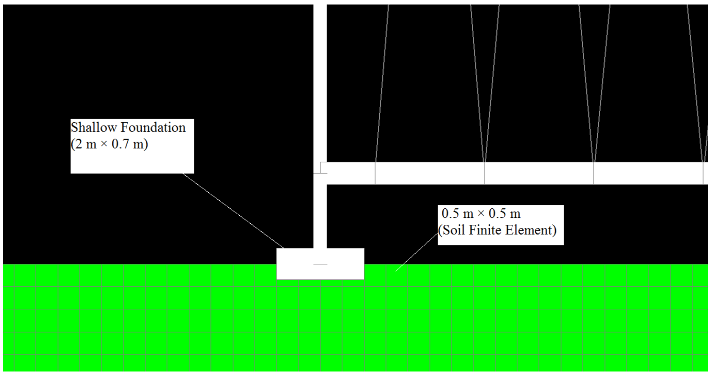
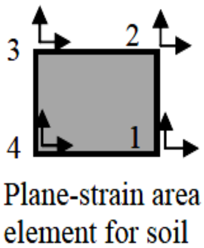


Figure 2-b. The soil-foundation model including soil finite elements

Finite elements of the soil material have been modeled as four-node two-dimensional plane-strain elements (see figure 3). Elements surrounding the foundation have been considered as squares with 0.5 m dimension and those which are far from the foundation have been meshed as 1×1 m^2 squares. Shallow foundations are modeled as frame (beam) elements in this paper. A Drucker–Prager model is selected for nonlinear behavior of the soil material [7] (see figure 4). This model is an elastic perfectly plastic model and in this paper, the input data for this model are the angle of friction and the angle of dilatation. In this research, dry sand with 34 degree friction angle and 4 degree dilatation angle is considered as the soil material. The cohesive parameter c is chosen zero because of mechanical parameters of sands. Modulus of elasticity and poison ratio of the soil material are assumed 55.2 Mpa and 0.45 respectively.



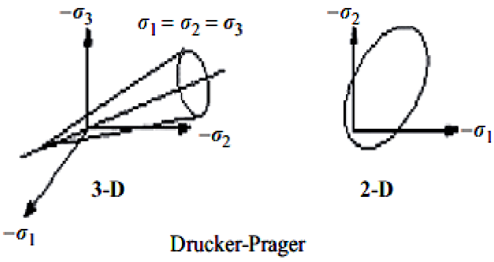


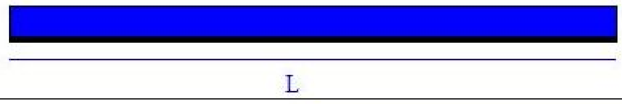
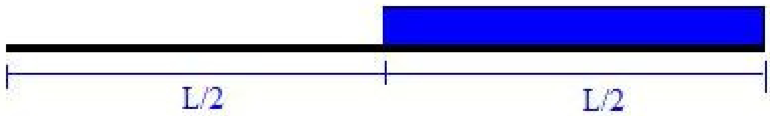
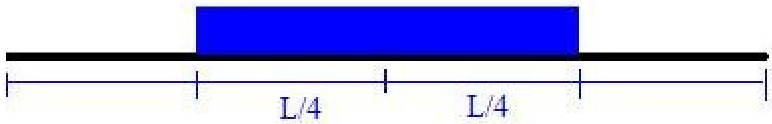
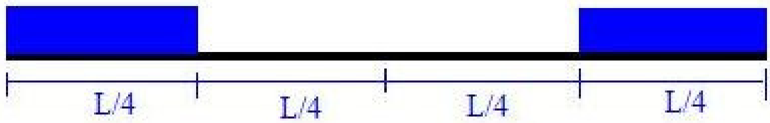
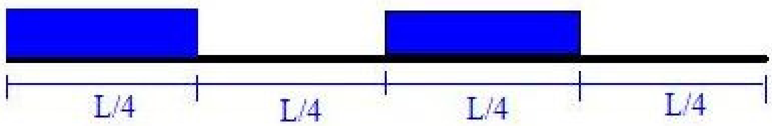
Figure 3. Soil finite elements

Figure 4. 3D and 2D stress figures of Drucker- Prager model

2.2. Loadings

Pedestrian suspension bridges usually experience several loads at different times. These loads may be due to pedestrians, bicycles, motorcycles, animals, or due to external loads such as earthquake and wind loads. In this study, the bridge was supposed to be subjected to live and dead loads statically. The live load was used symmetrically and asymmetrically as a distributed load with the amount of 210 kg/m. This amount is considered with respect to this assumption that there are three pedestrians placed on the unit length of the bridge's deck. In this research, the mass of one person is considered as 70 kg. The reason of considering three persons is having an excessive live load on the deck to be able to investigate slackness problem in hangers and soil effects on structural responses. The live load patterns applied in this research are shown in table 1. The amount of pre-stressed load of cables was considered based on the weight of cables, sag and axial stiffness in cables. In this paper, a nonlinear static has been used to investigate nonlinear behavior of the suspension bridge with respect to soil material effects relying under the structure [1, 2].

Table 1. Applied Live Loads Due to Pedestrian Vertical Loads

Pattern Name of Load	Loaded Length (m)	Intensity of Gravity Loads (kg/m)	Load Pattern
A	100	210	
B	50	210	
C	50	210	
D	50	210	
E	50	210	

III. Results and Discussions

The five considered pedestrian loads on the bridge have been applied for statically comparing and also modal performances of the suspension footbridge once without soil-structure interaction and another with considering the soil-structure interaction. In the case of static behavior of the structure, some responses such as hanger forces, slackness, overstress and oscillations of forces which may cause fatigue or crack in cables have been compared for two considered models. Also axial forces in the main cable and axial forces, bending moments and vertical displacements in longitudinal beams have been investigated for two structural models. In the case of modal behavior of the footbridge with and without soil consideration, some important natural modes and frequencies have been compared for both models. The modal behavior of suspension footbridges can be sensitive to the soil-structure interaction and important when dynamic pedestrian loads will be applied on the deck. In this research, a modal comparison especially in the case of resonance probability is represented between the footbridge with and without soil effect with respect to some natural modes and frequencies of the footbridge which are prone to be synchronized by pedestrian load frequencies.

3.1. Static Investigations of Two Models

3.1.1. Comparison of the Analysis Results for Hangers in Two Models

Under the A load pattern represented in table 1, the analysis of the bridge without soil effect showed that the slackness problem occurred in many hangers especially at the first and end of the bridge's deck while it did not occur in the structure with soil effect (see Figure 5). Also analysis showed that hanger forces of the first model are greater than forces of the second one. It can be observed according to figure 5.

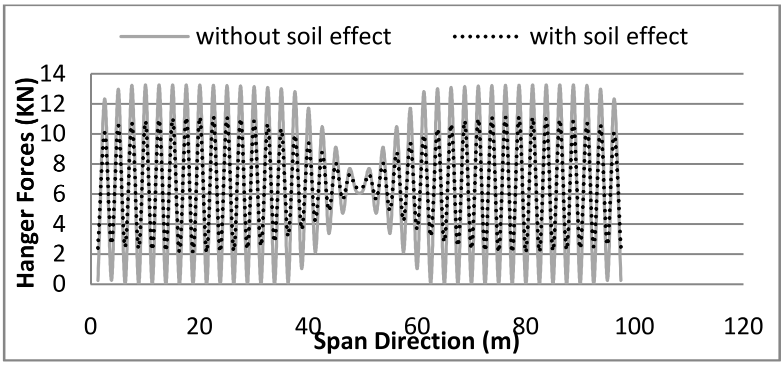


Figure 5. Hanger forces of the footbridge with and without soil influence under load A

In the case of both models with and without soil-structure interaction, when B load pattern is applied on the deck there are many slacked hangers but their number in the second model (with soil influence) is a little more than the number of slacked hangers in the first model (without soil influence). Figure 6 shows the hanger forces for load B along the bridge's span.

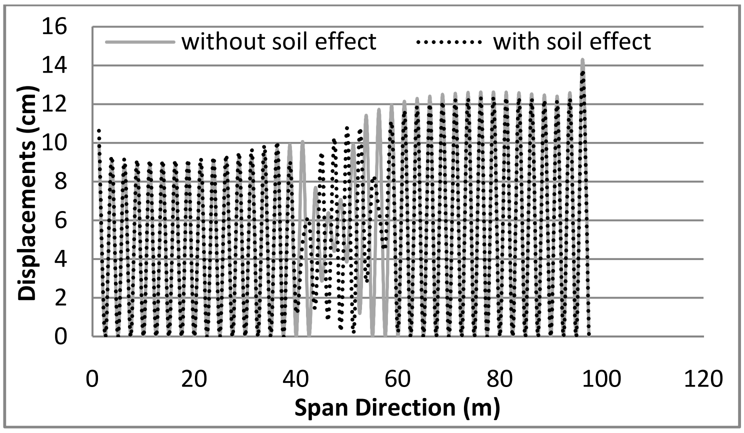


Figure 6. Hanger forces of the footbridge with and without soil influence under load B

Also with respect to other load patterns (C, D and E), it seems that hangers will be subjected to the slackness too. Figures 7, 8 and 9 refer to the hanger forces and slackness locations along the footbridge's span under load patterns C, D and E respectively. In general, because of orientation of two adjacent inclined hangers, slackness problem appears in one of them and overstress in another. This can be observed according to all figures represented in this section.

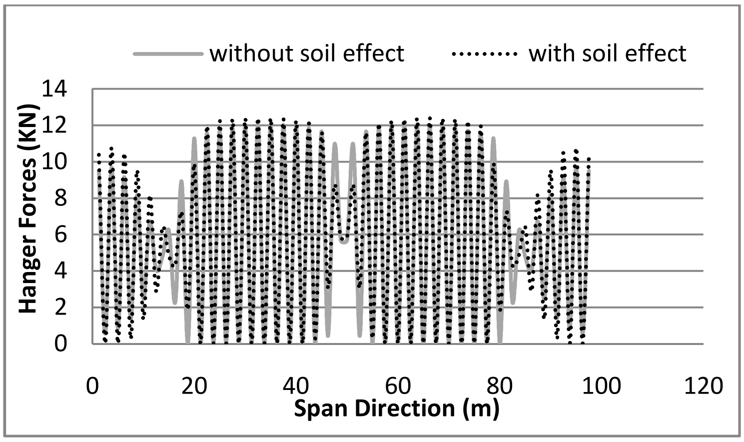


Figure 7. Hanger forces of the footbridge with and without soil influence under load C

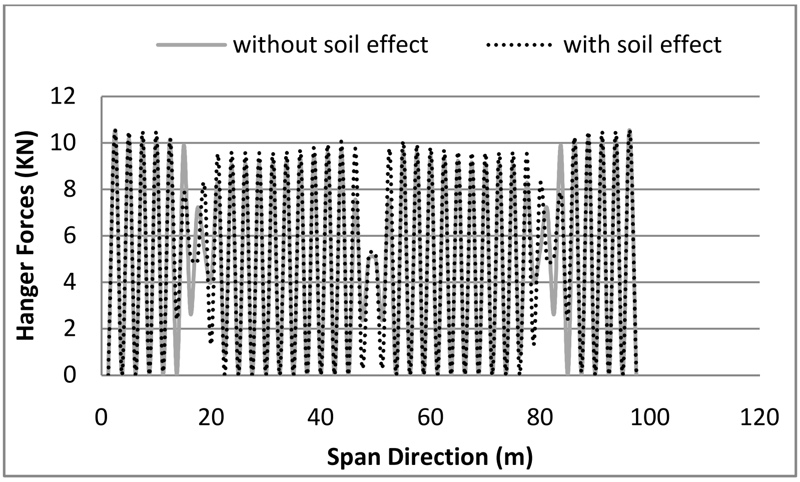


Figure 8. Hanger forces of the footbridge with and without soil influence under load D

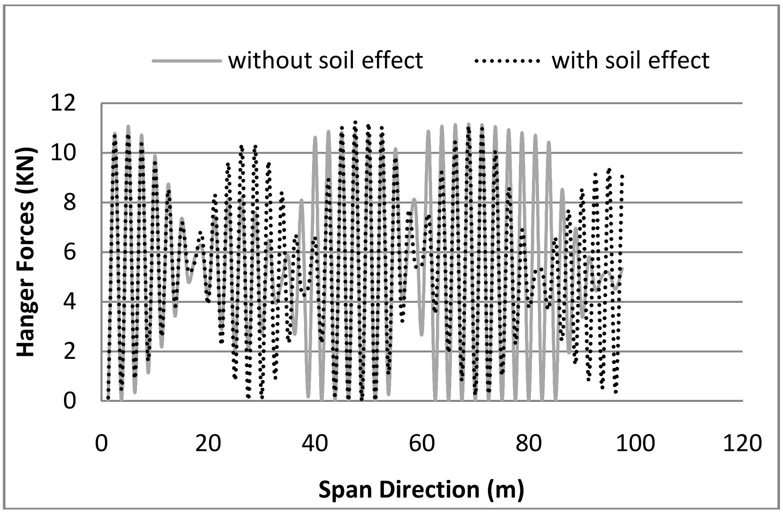


Figure 9. Hanger forces of the footbridge with and without soil influence under load E

The results of hanger forces and slackness are given in table 2. In this table, the number of slacked hangers, maximum hanger forces and percentage of force fluctuations are represented for the footbridge with and without soil-structure interaction with respect to the applied vertical loads. According to this table, the highest hanger forces are related to the load pattern B applied on the half of the deck. Also the most number of slacked hangers is related to the B load. There are 35 and 30 inclined hangers which are slacked under this load pattern in the models without and with soil-structure interaction respectively. As it is obvious from table 2, the number of slacked hangers in the model without soil consideration is more than the model with soil effect. This means that soil-structure interaction represents suitable responses when the hanger slackness and overstress problem are considered. Table 2 shows that hanger forces and slackness can be sensitive to the condition of foundations of the footbridge.

Table 2. Hanger responses for Pedestrian Static Loads

	Footbridge without soil effect				**Footbridge with soil effect**			
Type and pattern of load	Number of slacked hangers	Maximum tensile force	Amplitude of force fluctuations (percentage)		Number of slacked hangers	Maximum tensile force	Amplitude of force fluctuations (percentage)	
			from	to			from	to
A	24	13.265	-100	+89.5	-	11.119	-69.5	+59
B	35	14.316	-100	+192	30	13.790	-100	+176

C	22	12.044	-100	+101	22	12.409	-100	+107
D	30	10.551	-100	+111	28	10.556	-100	+111
E	16	11.154	-100	+123	3	11.261	-100	+125

The fluctuation of hanger forces is a suitable criterion to estimate probability of cable fatigue. When there is great amplitude of force fluctuations in hangers, it can be identified that after alternative loading and unloading conditions the hangers may be subjected to the fatigue problem. It can produce some structural disadvantages such as fracture, crack and et. in steel cables. According to table 2, the force fluctuations in hangers of the model with soil-structure interaction under loads A and B are less than amplitudes of the model without the soil effect. In the case of C, D and E loads, fluctuation amounts are relatively same together for both models.

3.1.2. Comparison of Forces in Main Cables for Two Models

One of most important structural members in suspension bridges is main cable. This member generally provides axial (tensional) stiffness under several kinds of external loads. It seems that soil material relying under the footbridge may influence on structural performances of main cables. In this section, the axial forces of main cables are compared for the footbridge with and without soil-structure interaction. Figures 10, 11, 12, 13 and 14 show forces of the main cable under loads A, B, C, D and E respectively. According to figure 16, the highest tension force of two models without and with soil effect is 623.95 KN and 628.795 KN. It can be observed that soil influence on the main cable forces and stiffness is considerable. As it is shown in figures 10 to 14, when the soil-structure interaction is taken into account, the tension forces of the main cable are greater than when the soil material is not considered.

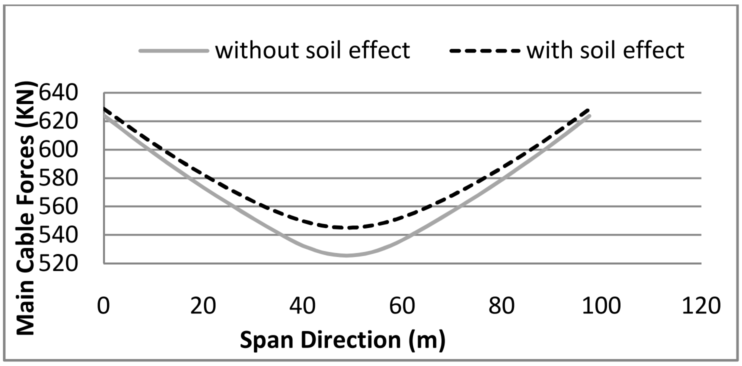


Figure 10. Main cable forces of the footbridge with and without soil influence under load A

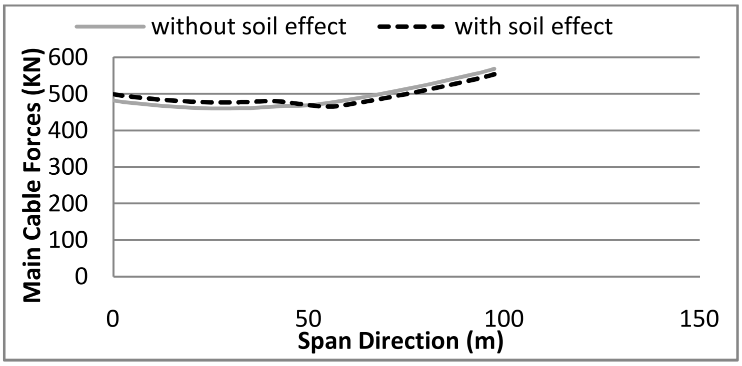


Figure 11. Main cable forces of the footbridge with and without soil influence under load B

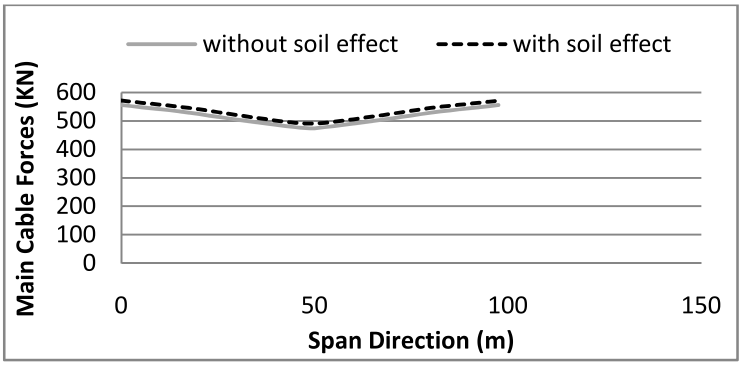


Figure 12. Main cable forces of the footbridge with and without influence under load C

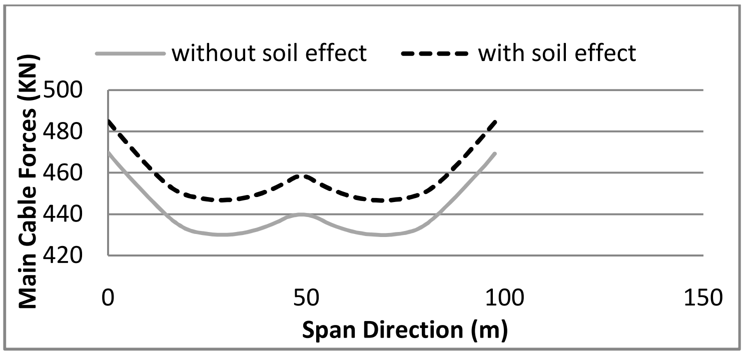


Figure 13. Main cable forces of the footbridge with and without soil influence under load D

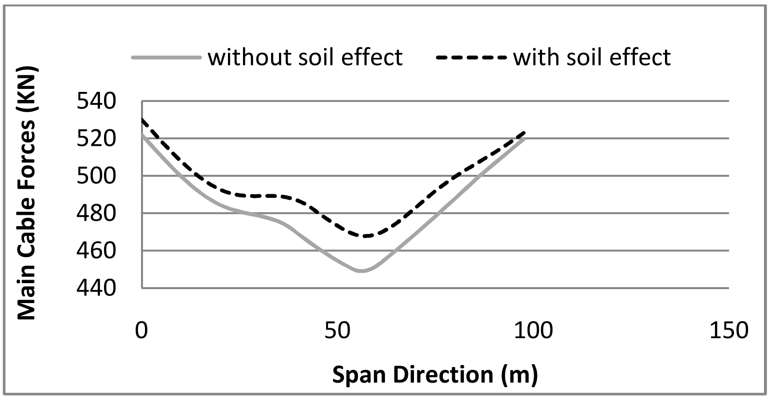


Figure 14. Main cable forces of the footbridge with and without soil influence under load E

3.1.3. Comparison of Vertical Displacements of the Deck in Two Models

According to the applied loads in this research (see table 1), it is reasonable to investigate vertical displacements of the deck because the loads due to pedestrians are assumed to be vertical and also the footbridge's deck is a sensitive member of it. However in this section, vertical displacements of longitudinal beams of two models with and without soil-structure interaction are compared in figures 15 to 19 with respect to live load patterns A, B, C, D and E. According to figure 16, the most vertical displacement of the bridge's deck is related to the load pattern B which is equal to -20.8 cm. Figure 15 shows that under load A, vertical displacements of the structure with soil-structure interaction are more than amounts of the model without soil considering. There is about 3 cm difference between the displacement values in both models. According to figure 16, displacement curves of two models are coincided relatively between positions about 25 m and 60 m from the left end of the span. In the case of load patterns C and E, vertical displacements of the model with soil-structure interaction are more than amounts of another model (see figures 17 and 19), but under D load displacements of the model with soil influence are more than another model's except corresponding amounts between positions about 35 m and 65 m from the left end of the span (see figure 18).

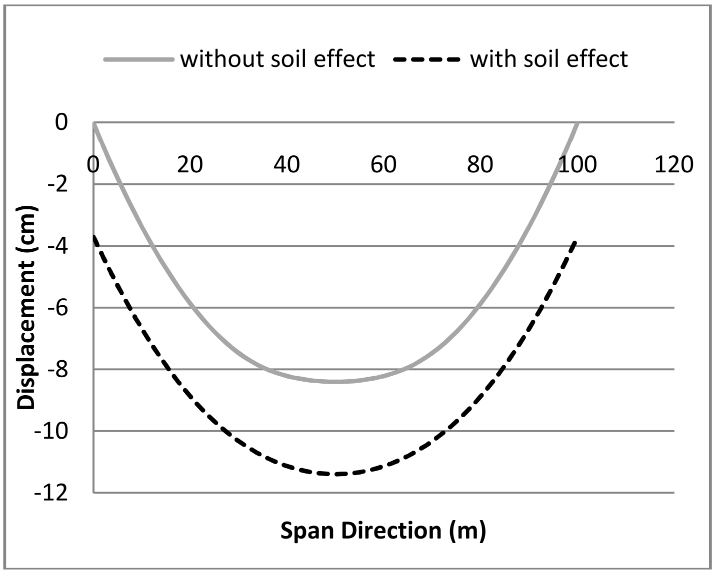


Figure 15. Vertical displacements of the deck for the footbridge with and without soil influence under load A

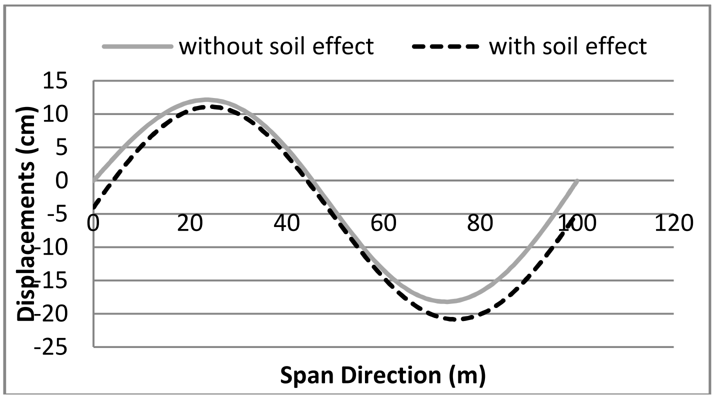


Figure 16. Vertical displacements of the deck for the footbridge with and without soil influence under load B

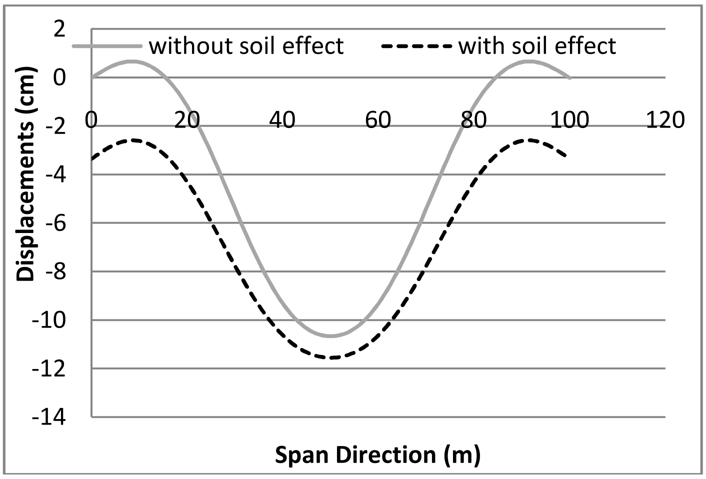


Figure 17. Vertical displacements of the deck for the footbridge with and without soil influence under load C

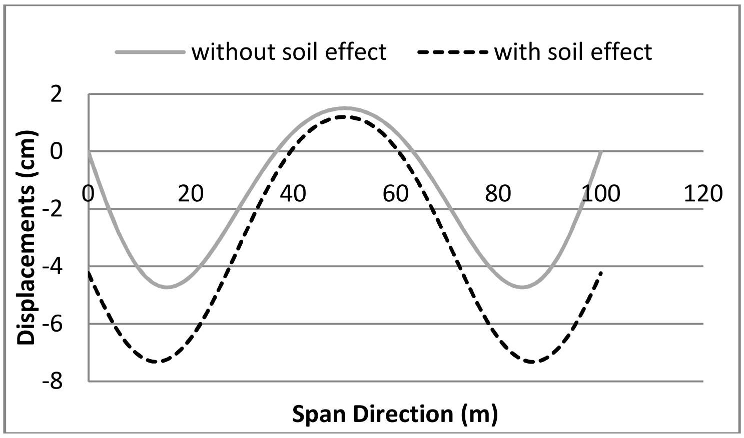


Figure 18. Vertical displacements of the deck for the footbridge with and without soil influence under load D

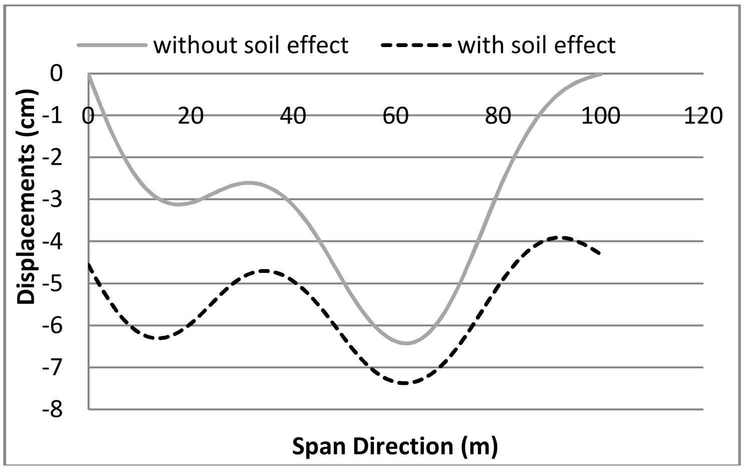


Figure 19. Vertical displacements of the deck for the footbridge with and without soil influence under load E

3.2. Modal Investigations of Two Models

3.2.1. Natural Frequencies and Vibration Modes of the Footbridge With and Without Soil-Structure Interaction

Natural frequencies and corresponding vibration modes are important dynamic properties. When a bridge structure is under synchronous excitation, it vibrates on its own natural frequency and vibration mode and is subjected to resonant vibration. In general, the structural stiffness of suspension bridges is mainly provided by suspending cable systems. The modal properties depend not only on the cable profile, but also on tension force in the cables, in which adjusting the cable tension and cable profiles can alter the vibration properties such as natural frequencies and mode shapes. However, in this research a modal analysis was carried out by considering soil-structure interaction in order to calculate the natural modes and frequencies of the footbridge (see figure 2) because as it has been observed in section 3.1.1 and 3.1.2, soil considering under the footbridge influences tension forces in hanger and main cable systems. Also a modal analysis is done in the case of the footbridge without soil-structure interaction (see figure 1). Dead load and pre-stressing loads of cables were considered for calculating natural frequencies. The natural frequencies might fall to a more or to a less critical frequency range for pedestrian induced dynamic excitation. The critical ranges for natural frequencies of footbridges with pedestrian excitation are shown according to tables 4 for vertical direction. In this research, all modes with frequencies which are in the critical range of frequencies (their resonance probability is very high) were investigated for the footbridge with and without soil-structure interaction. Table 5 shows natural modes and frequencies of the case study footbridge without and with soil influence respectively with the accompanying number of half waves and their description. In this paper, lateral modes are not investigated because a two-dimensional finite element analysis is carried out and also vertical direction of the footbridge is considered. Also, longitudinal modes are not very sensitive to resonance vibration.

Table 4. Resonance hazard levels for vertical vibrations

Frequency (Hz)	0,0	1,0	1,7	2,1	2,6	5,0 .....
Level 1			Maximum			
Level 2		Medium		Medium		
Level 3					Low	
Level 4	Negligible					Negligible

In this paper, first 10 natural modes of two models are investigated. According to tables 4 and 5, modes 1, 2 and 3 of the footbridge without soil-structure interaction with frequencies 1.35, 1.64 and 2.25 Hz are in the medium level of resonance hazard, but modes 2 and 3 are very close to the maximum level of resonance. In the case of the footbridge with soil-structure interaction (see table 5), modes 2 and 4 are in the medium range of resonance with natural frequencies 1.27 and 2.36 Hz but mode 3 with 1.83 Hz is coincided to the maximum range. However, this mode may be prone to synchronization with pedestrian vertically dynamic loads.

Table 5. Natural modes and Frequencies of Two Models

Footbridge without soil effect			**Footbridge with soil effect**		
Mode Number	Natural Frequency(Hz)	Number of Half Waves	Mode Number	Natural Frequency(Hz)	Number of Half Waves
1	1.3502	2	1	0.90701	2
2	1.643	3	2	1.2657	3
3	2.2521	3	3	1.8286	3
4	3.3337	4	4	2.3645	4
5	3.5283	-	5	2.833	4
6	4.2136	-	6	3.8919	-
7	4.7408	5	7	4.0149	5
8	6.3548	6	8	4.6485	6
9	8.1874	-	9	5.4814	6
10	8.229	7	10	6.6755	6

IV. CONCLUSIONS

Suspension footbridges are flexible structures because of flexibility behavior of their cable systems under external loads. This behavior can be sensitive to any changes in structural or nonstructural condition of footbridges. For example, amount and direction of external loads can be effective on responses. Also, support condition of bridge's can vary structural performances in suspension footbridges. However, some critical live loads due to pedestrians have been taken into account and also a soil material basement has been considered to investigate structural behavior of a suspension footbridge. This soil basement provides a soil-structure interaction and influences on structural responses of the structure. Therefore, two finite element models have been analyzed once without soil considering and another with soil influence on the structure then structural and modal responses have been compared:

- In the case of hanger responses, number of slacked hangers in the model without soil influence and under all the loads is more than their number in the model with soil-structure interaction. It means that if soil material is considered under the structure, inclined hangers will be mostly subjected to slackness problem. Also, the maximum hanger forces under considered loads in the model without soil are greater than another model. Force fluctuations in hangers of the model with soil-structure interaction under loads A and B are less than amplitudes of the model without the soil influence. In the case of loads C, D and E, fluctuation amounts are relatively same together for both models. However, it is convenient to take into account soil-structure interaction to analyze and design suspension footbridges.

- The suspension footbridge with soil influence results greater forces in the main cable in comparison with the structure without soil considering. It can be observed for all the considered loads. The main cable can bear additional resulted forces because of a main role of it in stiffness of the suspension footbridge.
- One of sensitive structural members in suspension footbridges is longitudinal beam which stiffens the bridge's span against extensive loads and displacements. In this research, it can be observed that the model with soil-structure interaction results greater vertical displacements in comparison with the model without soil influence. It seems because of foundation settlements under the vertical loads.
- In the case of modal behavior of two models (with and without soil-structure interaction), soil considering in modal analysis varies natural modes and frequencies of the footbridge. In this research, natural frequencies of the footbridge with soil-structure interaction decrease in comparison with another model and one of frequencies of it intends to the maximum hazard level of resonance vibrations. With respect to the footbridge without soil influence, there are three natural frequencies which coincide on the medium hazard level of resonance. However, modal results shows that taking into account the soil influence under the structure plays a main role in dynamic characteristics of the footbridge.

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