Seismic response of cable-stayed bridge subjected to single-support excitation on various soil condition

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Abstract. For cable-stayed bridge, pylon and girder are one of the most important factors in the design process. Because of the length this structure, it needs to consider the type of the soil because different soil type can be resulting a different earthquake loads. In this study, the behavior of superstructure was investigated using time history analysis subjected to excitation uniformly on the pylon and girder. The test model was a cable-stayed bridge which classified as a long-span bridge. For obtaining the effects of soil type condition, different response spectrums are considered for three soil types: firm, medium, and soft soil. The response spectrums were thus converted to become ground acceleration time history and displacement time history. The displacement was then applied longitudinally and transversally to the supports of the structure to determine the behavior of the bridge. The result shows that the maximum displacement on the pylon and girder due to longitudinal load was at the top of the pylon and in the middle of the main span. As for the transverse earthquake load, the maximum displacement was in the middle area of the pylon and the middle of the main span. The results also defines that the displacement caused by firm soil is smaller than medium soil and soft soil.

1 Introduction

Bridge is the most important tool in connecting the social and economic needs of society. It has so many functions to ensure the comfort and safety of the community. Earthquake is known as an important load that a bridge should resist. Thus in design, the area of the earthquake zone must be highly considered. Especially when the span length of the bridge increases, cable-stayed bridge become susceptible to environmental action and more difficult in design [1]. Earthquake is a pounding caused by release energy of ground motion in the earth. Earthquake is endogenous that can suddenly release and damage areas in a short time [2].

The cable-stayed bridge is one of the most elegant structures simply because this structure has many configuration choices when designed. For example, it has a variety of arrangement of cables such as fan, harp, and semi fan types [3]. Cable-stayed bridge construction is categorized as efficient, economical, and stays of the bridge have been proven to decrease costs in the construction of medium to long-span bridge [4]. In addition, this elegance and the economic bridges are very competitive in a wide range of span length that was insurmountable in the past. Moreover, this bridge can be constructed with a super long-span up to 1000 m, and it seems that in the future, this limit will improve [5].

The cable-stayed bridge is a stable structure to resist the seismic in principle. First, it is a flexible structure, so that provides long periods to decrease a level of spectral acceleration. The second cable-stayed bridge can decrease a support reaction and vulnerability of structure in seismic load, so that reduces the displacement in the deck [4].

To determine the effect of seismic load on the structure, an ideal model submitted by practical technicians to estimate the structure is excited uniformly from ground motion due to seismic load. However, the spectral acceleration of earthquake change while moving, However, a varying level of spectral acceleration in short time is neglected. Based on this assumption, an analysis method on the structure is excited uniformly and know as uniform support excitation (USE) and used in the analysis [6].

Furthermore, when the structure is excited due to seismic load, the response and ground displacement are interdependent. In Earthquake, the seismic wave is transmitted from bedrock through the soil into the new structure. Generally, the response of structure depends on soil property, characteristics of dynamic excitation, types of foundation, and structure characteristics [7]. Analytical Evaluation of seismic load in a specific location is unavoidable because it is more simplification needs to generate a solution. Also, what method used in the analysis, uncertainty due to idealization soil behavior and dynamic design parameter always affect the model [1]. This paper is presented the time history method with converting the spectral acceleration to load-displacement and considering the soil condition that excited uniformly to determine the behavior of the structure.

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2 Description of bridge

2.1 Bridge structure

A model cable-stayed bridge used is a long-span bridge, consist of 3 spans (2 pylons) with total span length is 642 m (146m+ 350m+ 146m). The height of the tower is 84 m, and meanwhile the height of the piers is 39 m. This bridge has a composite deck with longitudinal and transverse girder is connected and slab above it. The slab section is 0.25 m, with a width of 21.5 m. The composite deck in each bridge is supported by 14 cables per half span. The arrangement of cables is a fan type in longitudinal and two-planes systems in transverse. This cable has various areas from 383.1 mm^2 to 1149.3 mm^2 with a distance 12 m on each composite deck (24 m to146 m), 8 m in each composite deck (8 m to 24 m), and 2 m on the top pylon. The connection between the pylon and composite deck is suspended on it. Foundation of this bridge is a bored pile that is considered rigid to the ground. The configuration can be seen in Figure 1.

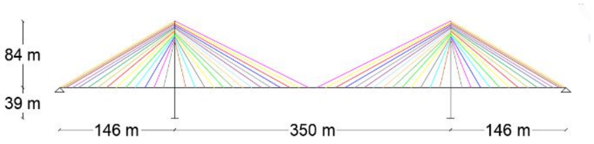


Fig. 1.The bridge upper structure model

2.2 Finite element method

Based on the ultimate design scheme of this long-span bridge, the structure is modeled by structural analysis software that is shown in Figure 2**.** In this model, a straight frame is simulated as a girder and pylon. Then, the area is simulated to the deck, and the cable is chosen to simulated as a cable element. The restraint between deck and pylon are suspended. A combination of dead load and load-displacement is determined on the model. In order to compare the behavior of the structure due to lateral load, thus load displacement of various soil condition are excited uniformly throughout the structure. The condition of soil used is obtained from soil site classification, that is soft soil, medium soil, and firm soil.

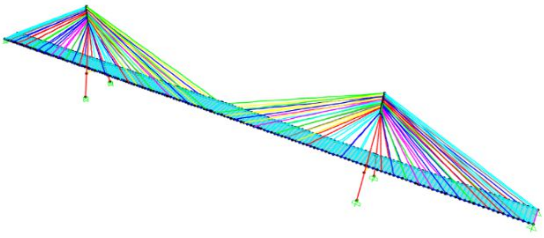


Fig. 2. Finite element model of the bridge

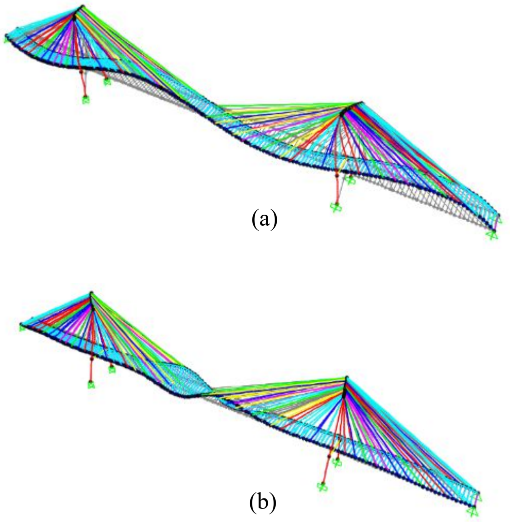
2.1.1 Mode analysis of bridge

Mode analysis of the bridge is conducted by structural analysis program by iteration method. Ten typical mode shapes with natural period are presented in Table 1, and two modes of shape are shown in Figure 3.

Table 1. Typical modes of the bridge in the main girder

No	Frequency/Hz	Mode Shape
1	0.669	First symmetric lateral motion (S-L.1)
2	0.836	First asymmetric lateral motion (AS-L.1)
3	0.990	First asymmetric vertical motion (AS-V.1)
4	0.992	Second asymmetric vertical motion (AS-V.2)
7	1.339	First asymmetric torsional motion (AS-T.1)
8	1.407	First symmetric vertical motion(S-V.1)
9	1.431	Third asymmetric vertical motion(AS-V.3)
10	1.667	Fourth asymmetric vertical motion (AS-V.4)

Note: AS-Antisymmetric; S-Symmetric; V-Vertikal; L-Lateral; T-Torsional. The number show the order



(a)

(b)

Fig. 3. Typical mode shape of the bridge

3 Single-support excitation method

There are three methods used to analyze long-span bridge, response spectrum, time history, and random vibration method. The response spectrum method based on the excitation of SDOF is widely used, but it is difficult to acquire accuracy in seismic analysis. Time history is more accurate analysis method than the other two methods but requires complex calculation [8].

There are two methods in analysis structure in time history analysis method. In the first method, the displacement time history is subjected to the structure as soil excitation, and the dynamic equation is derived according to ground displacement in the absolute coordinate. On the second method, acceleration of time history is put as soil excitation of the structure under, and the dynamic equation is derived according to ground acceleration in the absolute coordinate [9]. To determine the dynamic equation of structure under seismic load, the freedom of structure is divided into the freedom of superstructure and base, thus can be written as :

$$\begin{bmatrix} M_{ss} & M_{sb} \\ M_{sb} & M_{bb} \end{bmatrix} \begin{Bmatrix} \ddot{x}_s \\ \ddot{x}b \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{sb} & C_{bb} \end{bmatrix} \begin{Bmatrix} \dot{x}_s \\ \dot{x}_b \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sb} \\ K_{sb} & K_{bb} \end{bmatrix} \begin{Bmatrix} x_s \\ x_b \end{Bmatrix} = \begin{Bmatrix} 0 \\ R_b \end{Bmatrix} \qquad (1)$$

Where, $\ddot{x}_s$, $\dot{x}_s$, and x_s are the motion vectors of the superstructure in the absolute coordinate; M_{ii}, C_{ii}, K_{ii}, are the matrix of mass, damping, and stiffness, and index ss, bb, and sb are the freedom of the superstructure, base, and combination of their items. R_b is the reaction of the structure; if the response has been acquired, R_b can be calculated into equation (1). Thus, the dynamic equation $\ddot{x}_s$, $\dot{x}_s$, dan x_s can be written :

$$M_{ss}\ddot{x}_s + C_{ss}\dot{x}_s + K_{ss}\, x_s = -(M_{sb}\ddot{x}_b + C_{sb}\dot{x}_b + K_{sb}x_b) \qquad (2)$$

If the model is used in lump mass. So, M_{sb} is equal to zero, the damping matrix is hard to calculate, and the force of damping $-C_{sb}\dot{x}_s$ can be neglected. Thus the equation can be simplified to be :

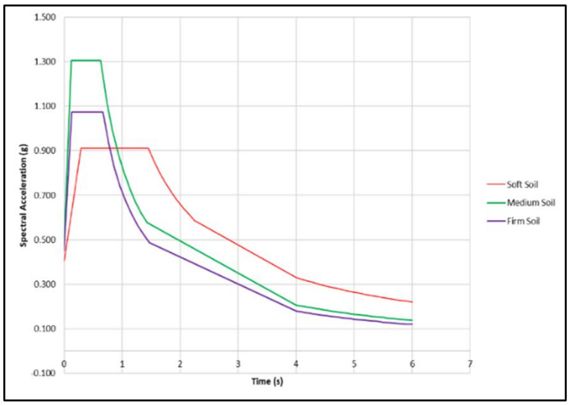
$$M_{ss}\ddot{x}_s + C_{ss}\dot{x}_s + K_{ss}\, x_s = -(K_{sb}x_b) \qquad (3)$$

Where x_b is the ground motion vectors, $-K_{sb}x_b$ is the force of superstructure due to ground motion in absolute coordinate.

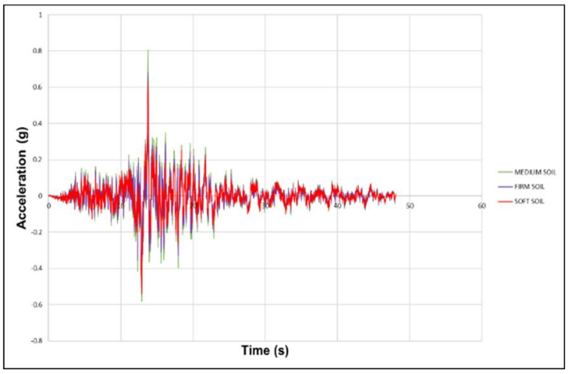
4 Spatially ground motion

For this study, the acceleration of ground motion used in the analysis is 0.6g, and site class is four based on the seismic code of bridge. The ground motion is acquired from the seismic map, then adjusted to the acceleration of time history within interval 0.01 second using Etabs, as shown in Figure 4.

On the second method, the displacement of the time history is subjected to the structure as ground excitation. Thus, the acceleration of time history is adjusted to displacement using Seismosignal. The excitation is put on each restraint of the structure, and throughout the model is excited uniformly. The structure model is then calculated with different soil types. The spatially of ground motion are shown in Figure 5.



(a). response spectrum



(b) time history

Fig. 4. Response spectrum to time history adjustment

The displacement of the time history is obtained from integrating the acceleration. The calculation of acceleration integration of firm soil, medium soil, and soft soil is 66.22 cm, 58.20 cm, 45.31 cm, respectively, as shown in Figure 6.

5 Seismic analysis of bridge model

The dynamic response of the bridge model is calculated in various soil types. The structure is excited uniformly, depending on the analysis parameter need, and from the calculation, there is a difference in each model.

5.1 Longitudinal ground motion

The bridge model is subjected to ground motion in a longitudinal direction. The models are then analyzed in longitudinal displacement.

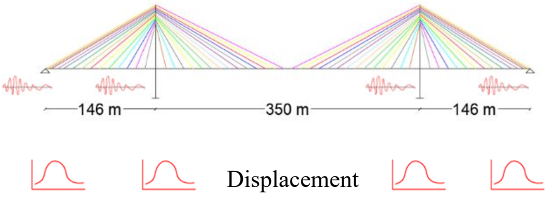


Fig. 5. Single-support excitation of the bridge model in various soil types.

From the analysis, the maximum displacement of the pylon is obtained in connection with the shortest cable between pylon and girder. and firm soil are 1017.3 mm, 813.81 mm, and 700.02 mm, and pylon II is 1019.20 mm, 815.72 mm, and 701.90 mm as shown in Figure 7.

Furthermore, the maximum displacement of the girder is obtained in the main span bridge. The displacement in the soft soil, medium soil, and firm soil are 742.57 mm, 590.51 mm, and 508.05 mm in the middle of the main span bridge, as shown in Figure 8.

5.2 Transverse ground motion

For this model, the bridge is excited in transverse ground motion. The models are then analyzed in transverse displacement. The result shows that both pylons have an equal displacement, where the maximum is obtained in the top of the pylon or on the longest cable connection between pylon and girder. The displacement is acquired from soft soil, medium soil, and firm soil are 908.57 mm, 740.77 mm, 633.61 mm Figure 9.

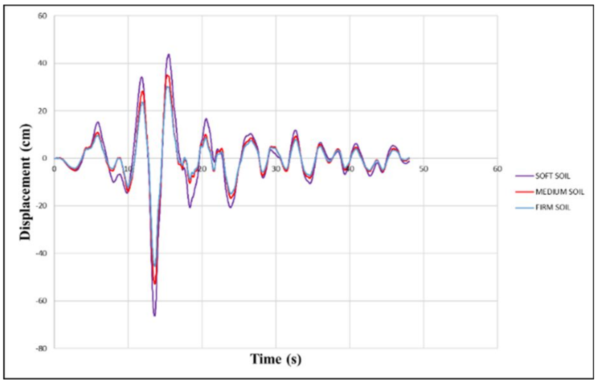
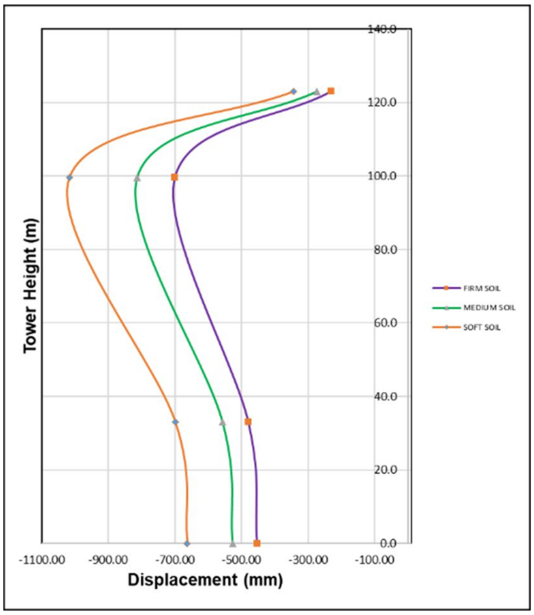
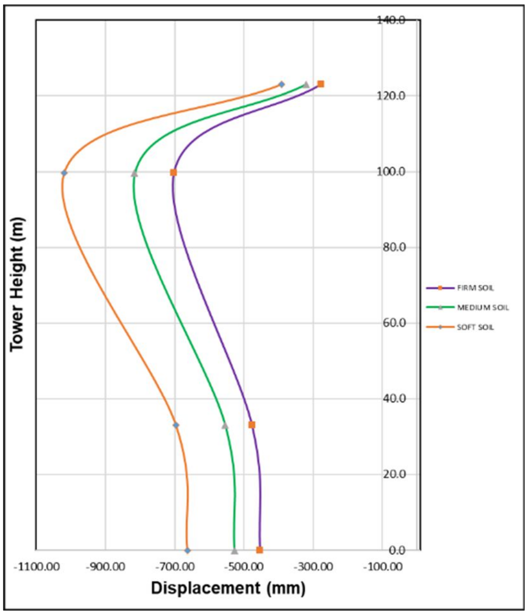


Fig. 6. The displacement of in uniform excitation.



a. Pylon I



b. Pylon II

Fig. 7. Longitudinal displacement of the pylon

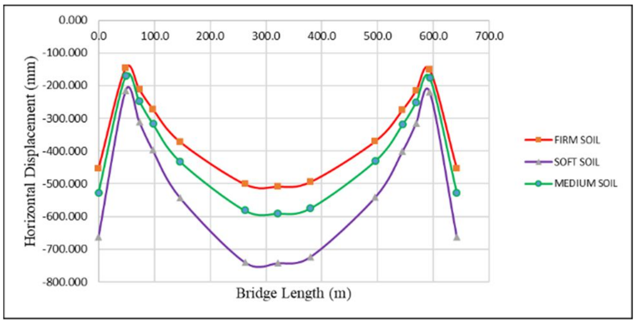
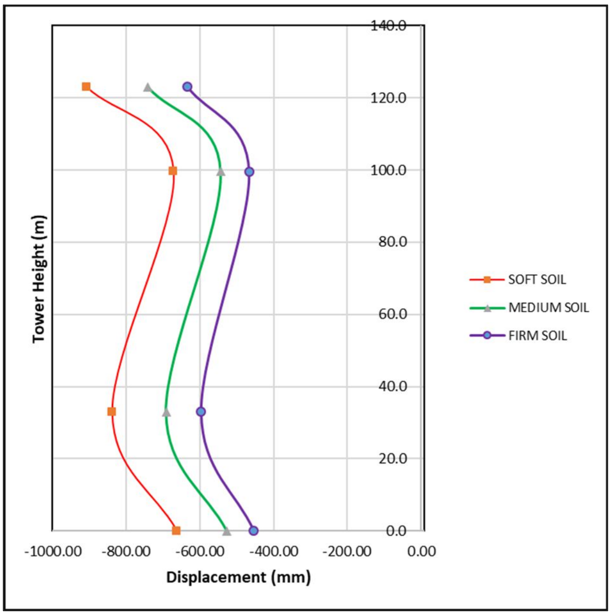
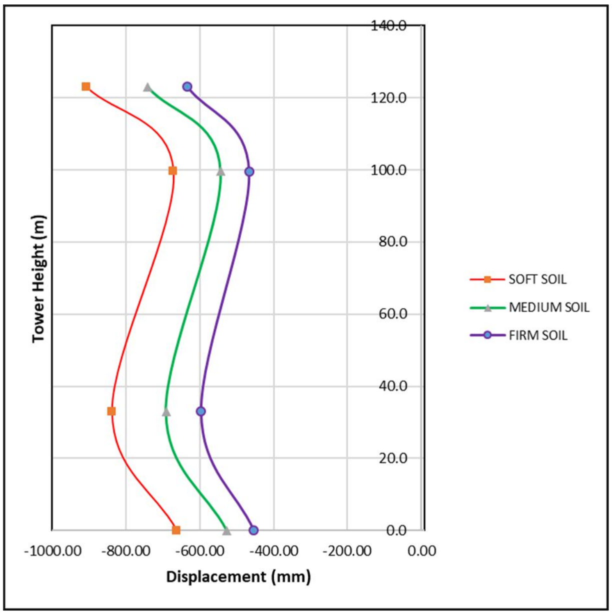


Fig. 8. Longitudinal displacement of the girder



a. Pylon I



b. Pylon II

Fig. 9. Transverse displacement of the pylon

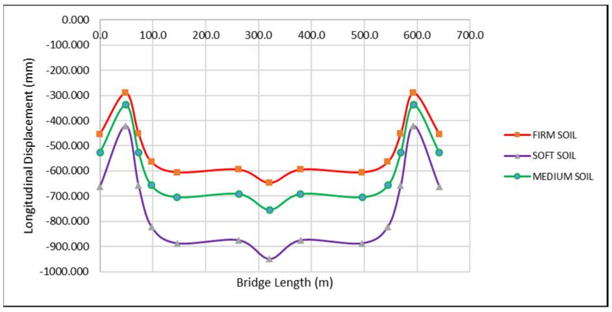


Fig. 10. Longitudinal displacement of the girder

In the girder, the maximum displacement is in the middle of the main span. From the calculation, the behavior of the girder is equal to each soil type. The middle of this main span is not supported by stays cable, thus induce a significant displacement. The displacement of soft soil, medium soil, and firm soil are 948.97 mm, 753.89 mm, 647.47 mm, as shown in Figure 10.

6 Conclusions

This study is aimed to investigate the seismic behavior of cable-stayed bridge under single-support excitation considering the variety of soil. Based on result, conclusions are made as :

1. The analysis of the cable-stayed bridge acquires a significant displacement on the pylon and girder. The maximum displacement is obtained by soft soil, medium soil, firm soil, respectively.
2. In longitudinal ground motion, the maximum displacement of the pylon is in the shortest cables connection between girder and pylon. Then, the maximum displacement of the girder is in the middle of the main span.
3. In transverse ground motion, the maximum displacement of the pylon is an equal value on the top of a pylon or in the longest cables connection between pylon and girder. Then, the maximum displacement of the girder is in the middle of the main span bridge, where cable stays do not support the girder.

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