Analysis of suspension bridge response due to earthquake under different soil conditions

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Abstract. A suspension bridge is a long span bridge that has the advantage of the possibility of not having a pillar in the middle and using cables as the primary load bearer. Due to its long spans, the analysis of the bridge should be treated very carefully, especially under an earthquake. The earthquake that occurs will cause ground movement to affect the performance of the bridge structure. Furthermore, various soil conditions will also cause the existence of the bridge structure to experience differences. In this study, a super long-span suspension bridge is analyzed under different soil conditions. It is assumed that each support of the bridge is on the same ground condition and has a uniform ground movement. The bridge is then analyzed relating to the response of the bridge structure due to a uniform earthquake in the form of internal forces and displacement both in terms of static and dynamic analysis. Results show that soft soil induces a more massive internal forces response structure compared to hard soil.

1. Introduction

Indonesia is an archipelago country which has a high population and various topographical conditions. Therefore, supporting facilities are needed to ease the accessibility of the mobility of the population with such conditions. One of the supporting facilities is a bridge. In general, a bridge can be interpreted as a land transportation infrastructure that aims to connect two areas cut off by several obstacles, such as valleys, hills, rivers, ravines, lakes, sea, irrigation channels, railways, or roads that cross not in a plot. Compared to other bridges, the advantage of a suspension bridge is that it has a relatively long span without using a pillar in the middle. Indonesia itself is an area that is prone to earthquakes because of its position on the Pacific Ring of Fire. Along the ring path, many active volcanic chains and tectonic plates continue to move and collide with each other to this day. This condition resulted in the area traversed by the path experiencing ground movement. This research will analyze how the suspension bridge structure against the earthquake loads on different soil types.

A suspension bridge is a bridge where the structure uses cables as the main structural element that carries traffic loads. It can also be interpreted that the girder is supported directly by the tower, through cables, and is used as its primary structural element.

The suspension bridge has been around since the 18th century in 1825, namely the Menai Straits suspension bridge in England. The bridge construction still used stone towers and cables from iron chains that function to hang the highway. In 1939 the cables from the iron chain were replaced by steel bars. Then after that, the Niagara suspension bridge was built in the United States. The construction of this bridge is slightly different because it is designed with two decks, namely the upper deck for
railroad roads and the lower for road traffic. This deck is a "stiffening truss" made of wood. With continued research by engineers on suspension bridges, steel bar chain cables changed to the steel cables used in the Brooklyn suspension bridge in the United States in 1867. A special feature of this bridge is that the cables from the towers hang from the deck and are more stable to the wind. Then along with the development of technology, suspension bridges are increasingly developing with varying shapes in materials and aesthetics. [1,2] Two picture of suspension bridges can be seen from Figure 1.

(a). Menai Straits suspension bridge, United Kingdom
(b). Brooklyn suspension bridge, USA

Figure 1. Suspension bridges [2]

Earthquakes are a natural event in which a vibration wave occurs by shifting plates and results in shocks. The plates' displacement propagates through the ground and causes ground movement, which affects the structure of one of the bridges. Because there are differences in the level of earthquake hazard in a region, scientists carried out an analysis that then makes it a group of Indonesian territories in certain zones. The scientists present a map in the form of contour lines of bedrock acceleration, displayed with a graph of the period (T), which is called the response spectrum. It is known that the extent of the damage to structures caused by earthquakes is related to local soil conditions. Therefore, before constructing a structure, it is necessary to examine how the layers, which constitute the ground under and around the proposed structure, would behave during an earthquake. Suppose the structural damage during an earthquake results from complete ground subsidence that leads to massive scale displacement. In that case, the relationship between the structural damage and local soil conditions can obviously be seen. For example, the loose-grained ground may cause total and differential settlements from squeezing due to tremors and significant structural damage to buildings. It has been observed that during earthquakes, the dynamic stresses and pore water pressures on soft clay and sand layers cause massive landslides. The soil conditions contributing to earthquakes' damage are; soil amplification, soil liquefaction, landslides, and ground settlement [3][4].

Seismic waves propagation through near-surface soil layers can produce ground motions much more extensive and with different characteristics on the soil surface compared to those recorded at the rock base. The combined effect of earthquakes and local site conditions are commonly referred to as site effects. Those combinations of soil condition, structural models, and seismic excitations that lead to lower effective damping, will amplify the bedrock motion most significantly. For example, during the 1985 Mexico City earthquake, site amplification caused substantial damage and the collapse of many buildings. Numerous studies have also shown a correlation between damage and local geology and site condition [5].

2. Research Methodology

2.1. Description of case study
This case study uses a suspension bridge structure with a span of 920 meters. This bridge is fictitious and is considered to be in the city of Bukittinggi, Indonesia, which has a large earthquake probability. Figure 2 describes the dimension of the bridge.
The seismic analysis is conducted twice since in this research soils condition are considered. In other words, there are two cases applied in this study. The first case is that it is assumed the structure is standing on hard soil, and the second case is that the structure is considered to be constructed on soft soil. Because the soil of the site applied in both cases is different so that the earthquake excitation that comes to the structure will be different.

Figure 2. The configuration of the suspension bridge

Figure 3 shows the response spectrum for Bukitting for hard soil and soft soil. The earthquake applied to the supports of the bridge is conducted in two directions; elongated direction and transversal direction. The response spectrum data above only records the maximum response, whereas, in this study, the seismic loads need to be given a load at each point in time. Therefore, those response spectra will be converted into acceleration time histories, which will then be applied to all supports of the bridge. The acceleration time histories can be seen in Figure 4.
From the two graphs in Figure 4, it can be observed that there is a slight difference between hard and soft soil. The acceleration of hard soil is denser compared to soft soil.

3. Results and discussion
The seismic response of a structure is affected by its dynamic properties, and soil flexibility does not have an impact on it when the bottom soil of the foundation is supposedly frigid, and the soil flexibility is also ignored [6]. Therefore, in this analysis and discussion, the focus is only on the structure's internal forces, without considering the structure's seismic response.

After the suspension bridge has the earthquake loading arranged in the structure's longitudinal and transversal direction, the structural responses are analyzed. For this paper, three conditions of internal forces are discussed. Those are axial forces, shear forces, and bending moments around the side span of the bridge.

3.1. Axial forces at the girder
An axial force is a force that acts in the direction of the axis of a body. It can be compression or tension force acting in a member. This study investigates the differences between two different soil types to the long-span suspension bridges when the structure applied the earthquake load. The table below describes the values of axial forces that occurred in the right span of the bridge. The length of the right span (L) is 230 meters, and the points to be observed are three locations: 0.25L, 0.5L, and 0.75L from the support.

From Table 1, it can be seen that there are differences between the axial forces of hard soil and soft soil. The results obtained from hard soil cases are about ten percent larger compared to soft soil. This condition applies to both earthquakes given to the structure's elongated direction or its transversal direction.
Table 1. The value of axial forces for right span bridge

| Span (L=230m) | Hard Soil (kN) | Soft Soil (kN) | Percentage Hard/Soft Soil |
|---------------|----------------|----------------|--------------------------|
| Elongated earthquake direction | | | |
| 0.75 L | 34543.11 | 30814.20 | 10.79% |
| 0.5 L | 62611.41 | 55799.78 | 10.88% |
| 0.25 L | 76861.26 | 68611.34 | 10.73% |
| Transversal earthquake direction | | | |
| 0.75 L | 10377.76 | 9259.11 | 10.78% |
| 0.5 L | 18884.64 | 16841.08 | 10.82% |
| 0.25 L | 23252.25 | 20777.10 | 10.64% |

3.2. Shear forces at the girder

Shear forces acting on the girder of the suspension bridge are resumed in the table below. From the table below, it can be seen that contrary to the axial forces, shear forces on soft soil are more extensive compared to hard soil. The shear forces at the right side span for structure standing on soft soil are more than 50% larger than standing on the hard soil. This condition has happened for both earthquake comes to elongated or transversal direction. In the middle of the side span, the shear forces for hard soil are less for more about 20% than the shear forces existing on the soft soil.

Table 2. The value of shear forces for right span bridge

| Side Span (L=230m) | Hard Soil (kN) | Soft Soil (kN) | Percentage Hard/Soft Soil |
|---------------------|----------------|----------------|--------------------------|
| Elongated earthquake direction | | | |
| 0.75 L | 3135.83 | 4771.57 | -52.16% |
| 0.5 L | 1539.92 | 1822.53 | -18.35% |
| 0.25 L | 2367.90 | 2910.10 | -22.90% |
| Transversal earthquake direction | | | |
| 0.75 L | 10463.60 | 15917.99 | -52.13% |
| 0.5 L | 5158.39 | 6102.20 | -18.30% |
| 0.25 L | 7918.56 | 9731.46 | -22.89% |

3.3. Moment at girder

Table 3 describes the results of bending moments for the right span bridge.

Table 3. The value of bending moment for right span bridge

| Side Span (L=230m) | Hard Soil (kN) | Soft Soil (kN) | Percentage Hard/Soft Soil |
|---------------------|----------------|----------------|--------------------------|
| Elongated earthquake direction | | | |
| 0.75 L | 84083.30 | 108554.50 | -29.10% |
| 0.5 L | 161717.28 | 228266.35 | -41.15% |
| 0.25 L | 133522.1 | 186215.71 | -39.46% |
| Transversal earthquake direction | | | |
| 0.75 L | 284943.92 | 366851.97 | -28.75% |
| 0.5 L | 541859.71 | 763624.69 | -40.93% |
| 0.25 L | 447766.18 | 623448.05 | -39.24% |
It can be seen from the table that soft soils have a larger bending moment compared to hard soil. The largest discrepancy occurs at the middle of the side span, whereas the smallest happens in the ¼ of the span from right support.

From the results for the bridge's right-side span, it can be assumed that the differences in soil type will induce different results. This condition happens because the differences in dynamic loading resulted from different soil types. Different soil types will be yielding different spectral accelerations, as can be seen from the graphs below.

![Response spectrum comparison of soft, medium, and hard soil](image)

**Figure 5.** Response spectrum comparison of soft, medium, and hard soil

4. Conclusions
This simple study is relating to the internal forces observation in the right span of the suspension bridge. The bridge's loadings are coming from dead load and earthquake load, which is applied in a longitudinal or transversal direction. The bridge is assumed to be standing on firm and soft soil, and then the internal forces that happen are analyzed. From the result, it is concluded that soft soil will increase the internal forces in terms of shear and bending moments, whereas, for axial forces, hard soil will cause larger values than the soft soil. In other words, two points the same distance from an earthquake’s epicenter can experience significantly different effects. One may suffer over ten times the impact of another due to geological variations are known as site effects, which are based on two general characteristics; the softness of the soil or rock and the total thickness of the sediment above the bedrock. Although soil type is a significant predictor of an earthquake's effects, it is not the only factor. Other characteristics, like the fault’s orientation, irregularities in the rupturing fault surface, and dispersion of waves as they hit subsurface structures, can create spots of significant damage, and those hot spots are unique to each earthquake.

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