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The effect of ground borne vibrations from high speed train on overhead line equipment (OHLE) structure considering soil-structure interaction

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Abstract: At present, railway infrastructure experiences harsh environments and aggressive loading conditions from increased traffic and load demands. Ground borne vibration has become one of these environmental challenges. Overhead line equipment (OHLE) provides electric power to the train and is, for one or two tracks, normally supported by cantilever masts. A cantilever mast, which is made of H-section steel, is slender and has a poor dynamic behaviour by nature. It can be seen from the literature that ground borne vibrations cause annoyance to people in surrounding areas especially in buildings. Nonetheless, mast structures, which are located nearest and alongside the railway track, have not been fully studied in terms of their dynamic behaviour. This paper presents the effects of ground borne vibrations generated by high speed trains on cantilever masts and contact wire located alongside railway tracks. Ground borne vibration velocities at various train speeds, from 100 km/h to 300km/h, are considered based on the consideration of semi-empirical models for predicting low frequency vibration on ground. A three-dimensional mast structure with varying soil stiffness is made using a finite element model. The displacement measured is located at the end of cantilever mast which is the position of contact wire. The construction tolerance of contact stagger is used as an allowable movement of contact wire in transverse direction. The results show that the effect of vibration velocity from train on the transverse direction of mast structure is greater than that on the longitudinal direction. Moreover, the results obtained indicate that the ground bourn vibrations caused by high speed train are not strong enough to cause damage to the contact wire. The outcome of this study will help engineers improve the design standard of cantilever mast considering the effect of ground borne vibration as preliminary parameter for construction tolerances.

Keywords: Ground borne vibration, overhead line equipment, mast structure, vibration, soil-structure interaction

1. Introduction

Presently, due to rapid population growth, passenger journeys have increased by nearly 100% and freight by 60% (Baxter, 2015). The extra capacity provided is needed for economic growth in the future (RailCorp, 2011). The electric train has become the efficient railway systems. The electric train is allowed to run frequently and quickly. Overhead line equipment (also called "OHLE") is an equipment to supply power to make electric trains and consist of masts, gantries, and wires found along electrified railways. This is now the preferred means of powering trains throughout the world. Although the concept of OHLE is simple, the problem is the poor dynamic behaviour of OHLE (Beagles et al., 2016).

Due to the extreme environmental events and severe periodic forces, such as earthquakes in surrounding areas perhaps causing damage to the track and OHLE structure especially the mast structure, this can lead to the failure of the electrical system (Shing and Wong, 2008; Robinson and Bryan, 2009; Taylor, 2013). This is because when the frequency of ground motion matches the natural frequency of a structure, it will suffer the damage and large oscillations because of the occurrence of resonance effect (Ngamkhanong and Pinkaew, 2015). Apart from earthquake, ground borne vibration is a serious concern. One of the main sources of ground borne vibration on mast structures is trains passing. Railway vibration is a serious global concern as it can affect property and cause annoyance to people in surrounding area (Connolly et al., 2016). The vibration level depends on many factors such as train speed, ground condition, type of structure concerned etc. The effect of ground borne vibration on the building in surrounding areas has been studied in previous literature (Kouroussis et al., 2013; Zou et al., 2015; Zou et al., 2017; Vogiatzis and Mouzakis, 2017). Even though the ground borne vibration might not cause damage to the structure, this may cause annoyance to the people in the building (Suhairy, 2000; Lopes et al., 2016). Cantilever mast structures have not been fully studied. In practice, masts are designed as a fixed support with infinite stiffness. In reality, there is a small displacement created by the supporting soil. Based on the relevant literature (Prum and Jiravacharadet, 2012; NEHRP, 2012), different soil support conditions were taken into account. It was noted that soil-structure interaction affected the overall response of the structure. As for mast structure, it was noticeable that the rotational stiffness affected the natural frequencies and mode shape of vibration in a lower mode but rarely affected the higher mode (Ngamkhanong et al., 2017). This was because the dynamic behaviour was characterized by coincident eigenfrequencies, mode order change, while the eigenfunctions remain associated with the corresponding eigenvalues (Pierre, 1988; Benedettini et al., 2009; Sari et al., 2017). For most railway vibration problems, the predominant frequencies of the load spectra are normally in the range of 0.5Hz to 80Hz (Jonsson, 2000) depending on wheel-rail irregularities and vehicle effects (Kouroussis et al., 2014; Kouroussis et al., 2015). Therefore, this study considers the frequencies of ground borne vibration between 0Hz and 100Hz to cover all possible frequencies of ground vibration and the first-eight fundamental mode of mast vibration.

The present paper aims to study the effect of ground borne vibration generated by high speed trains on mast structures, with consideration of its underlying soil properties. Finite element model is employed to calculate the structural responses and the ground borne vibration is computed by the classical formulation based on the semi-empirical model for predicting low frequency vibration on soft ground condition (Kurzeil, 1979; Madshus et al., 1996). The obtained simulation results reveal that the train speed and soil condition influence the dynamic responses of mast structure.

2. Methodology

2.1 Modelling

In this study, the 3-dimensional finite element modelling is considered using a general-purpose finite element package STRAND7 (G+D Computing, 2001). OHLE is normally supported by lineside masts, typically made of H-section steel, with a fixed base. The catenary cable and the pull/push-off arms supporting the contact wire are attached to the ends of the cantilever. The modelling of cantilever mast structure is shown in figure 1, which consists of the two force members only. The young modulus of steel is 2x10^5 MPa with a density of 7850 kg/m^3. Poisson's ratio is 0.25.

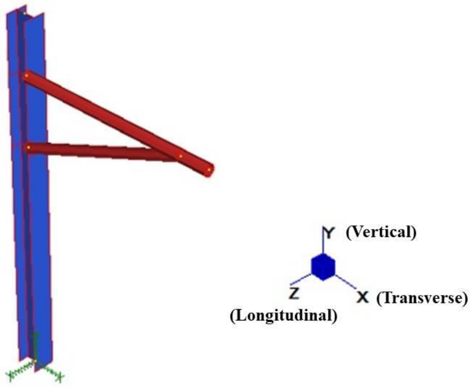


Figure 1 3-Dimensional model of OHLE

In this study, the translational stiffness in three directions is assumed to be fixed in order to restraint the translation displacement. Based on soil conditions, however, translational stiffness is not taken into account, and rotational stiffness of support conditions is varied from 1000kNm/rad to infinite (fully fixed support).

2.2 Ground borne vibration

Based on vibration measurements, it has been concluded that the factors that are of primary importance for the low frequency railway-induced vibration on the ground, and its effect in surrounding areas are as follows (Madshus et al., 1996): (1) Ground conditions, (2) Train type, (3) Line quality and embankment design, (4) Train speed, (5) Distance from track to structure, and (6) Building foundation and structure.

To conveniently calculate the level of ground borne vibration, the formula proposed by Madshus et al. (1996) can be used, as shown in Eq.1.

$$V = V_T F_s F_D F_R F_B \tag{1}$$

Where

V_T is a train type specific vibration level, F_s is a speed factor, F_D is a distance factor, F_R is a track quality factor and F_B is a building amplification factor.

F_s can be calculated as shown in Eq.2 where A is the train speed exponent, S is the train speed and S_0 is the reference speed on a standard track.

$$F_s = \left(\frac{S}{S_0}\right)^A \tag{2}$$

Distance factor,F_D, can be calculated as shown in Eq.3 where D is the distance from the centre of the track to the receiver, D_0 is the reference distance from the centre of the tracks and B is the distance exponent.

$$F_D = \left(\frac{D}{D_0}\right)^{-B} \tag{3}$$

The low frequency vibration peak can be observed dominantly in the softer ground (Madshus et al., 1996; Auersch, 2012) and thus it is assumed that high speed trains run along the track on soft ground. Therefore, the values used for ground vibration calculation are 0.1, 0.9 and 1.1 for V_T, A and B. In addition, vibration level on the ground at a reference distance of $D_0 = 20$m, from the centre of the tracks, when a train of the specified category passes at reference speed of $S_0 = 70$ km/h. It should be noted that the excessive vibration and degradation of surrounding soil can be detected at soft soil areas during high-speed train passage (Madshus and Kaynia, 2000; Vogiatzis, 2012)

The typical (F_R) used is 1.3 for old single track and structure amplification (F_B) is 1.3 for single storey buildings which are the best fit for single mast structure based on the height of structure. According to previous measurement on building (Mouzakis and Vogiatzis, 2016), it was interesting to note that the amplification factor indicated the increase in vibration up to 25Hz which covered the fundamental mode of vibration of mast structure.

It is assumed that the mast structure is located at a distance of 3.5m perpendicular to the track. The train speed varies from 100km/h to 300km/h. The ground vibration velocities created by train are inputted in both directions as seen in Figure 2. When the train moves on the track, the ground vibration has intensities depending on the distance or angle formed by track and distance from a train to the mast structure. The vibration is transmitted as Rayleigh surface waves in the propagation region to the structure. In this study, the different angles that create different distances from mast are considered as a vibration creation regions.

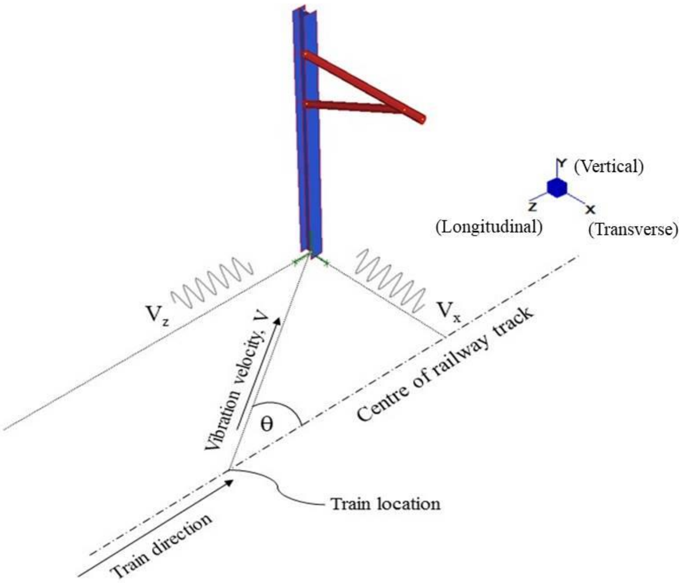
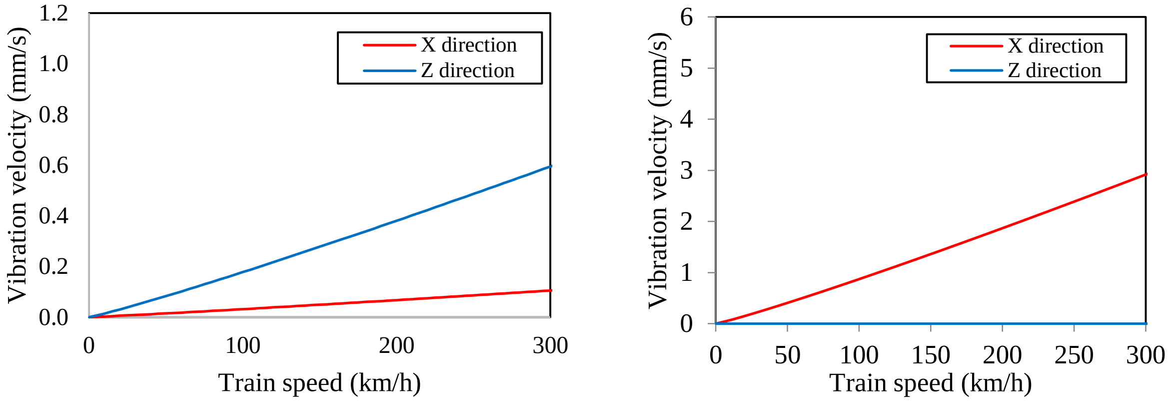


Figure 2 Location of the cantilever mast structure and direction of train on railway track.

The relationships between vibration velocity and train speed between 0km/h and 300km/h at the angle of 10 and 90 degrees are shown in Figure 3. As for 10 degrees, it can be seen that the vibration velocity in longitudinal direction is greater than that in transverse direction. Meanwhile, only vibrations in transverse direction can be observed when the train is located perpendicular to the track. The 3mm/s displacement in transverse direction can be observed at the train speed of 300km/h. It should be noted that the frequency ranges from 1 to 100Hz are considered in this study to cover the fundamental mode of vibration of the mast structure.



a) b)

Figure 3 Relationship between vibration velocity and train speed at a) 10 degrees b) 90 degrees

The ground-borne vibration velocity calculations in both directions are shown in Figure 4. In transverse direction, it can be seen that the vibration intensity increases when the train runs close to the mast structure. It should be noted that when the train is located perpendicular to the mast, the vibration velocity occurs only in transverse direction. The increase of angle leads to the higher vibration in this direction. As for the longitudinal direction, the ground vibration increases until the angle of the train reaches 45degrees and slightly decreases until the train is located perpendicular to the mast. This is because the vibration intensity is not dependent only on distance but other factors also play a role as stated in the previous section. In addition, the train speed increases and decreases with the same rate as ground borne vibration velocity. Therefore, the maximum vibration velocity occurs at the angle of 45degrees.

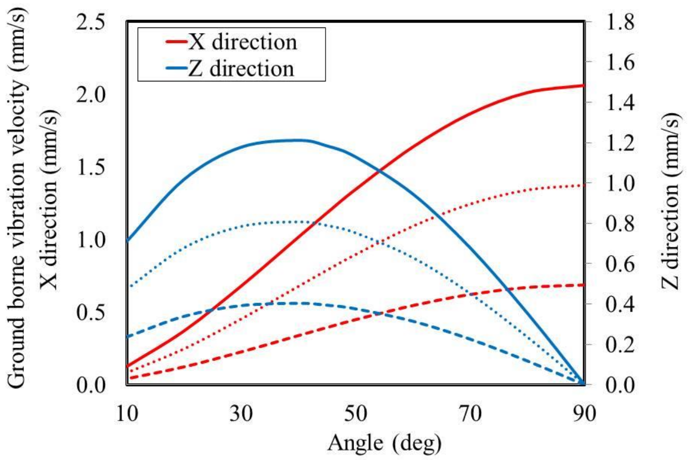
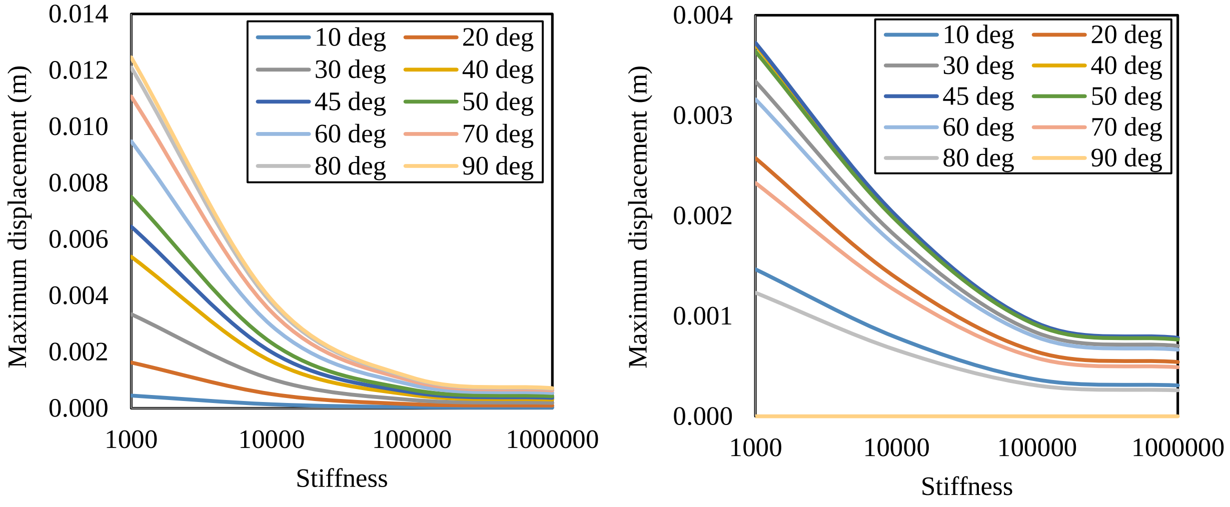


Figure 4 Ground borne vibration velocity at various distances from the track at a speed of 100km/h, 200km/h and 300km/h.

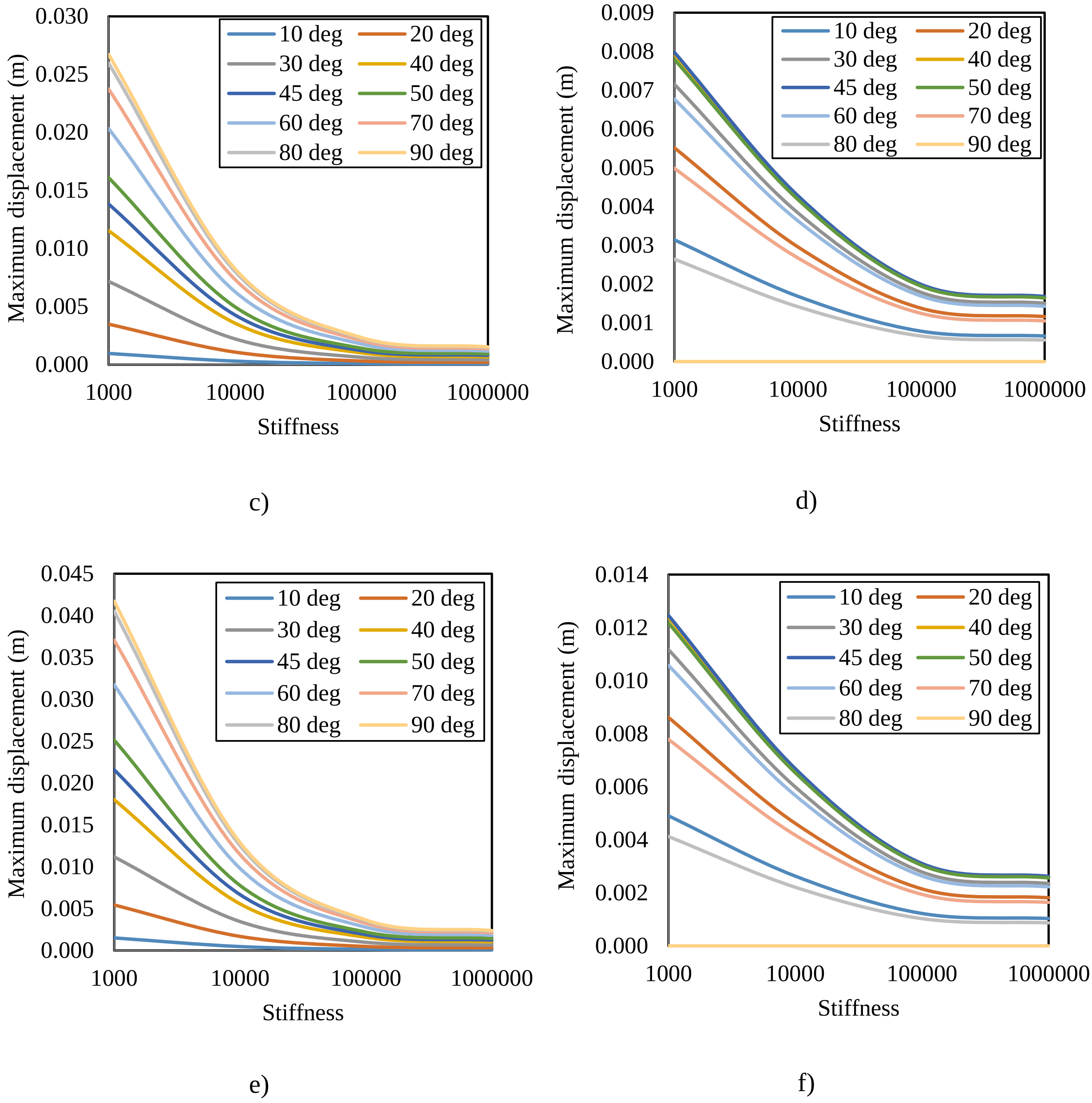
3. **Results and Discussion**

In this study, the frequency ranges between 1 and 100Hz are considered to cover the fundamental mode shapes of the mast structure. Based on previous study (Ngamkhanong et al., 2017), the first, second and third modes are twisting, bending about transverse, and bending about longitudinal, respectively. It was noted that the reduction of soil-structure stiffness associated with poor support and soft soil condition led to the decrease in natural frequency and the change of mode shapes in lower modes.

Figure 5 shows maximum displacement at the end of the cantilever mast, which is the location of overhead wire, in both directions at various soil stiffness. It can be seen that, for higher stiffness from about 100000kNm/rad to infinity, the displacements are very small compared with the lower stiffness. As expected, when the mast is located on the very poor support condition corresponding to the stiffness of 1000kNm/rad, the displacement is more than 5 times higher than that of the well support. In Figures 5a, 5c, 5e, it is clearly seen that when the train runs along the track, it can make ground vibrations and leads to the movement of mast especially in the perpendicular direction to the track. At the stiffness of 1000kNm/rad, about 40mm displacement can be observed when the train speed of 300km/h passes the mast at an angle of 90 degrees.



a) b)

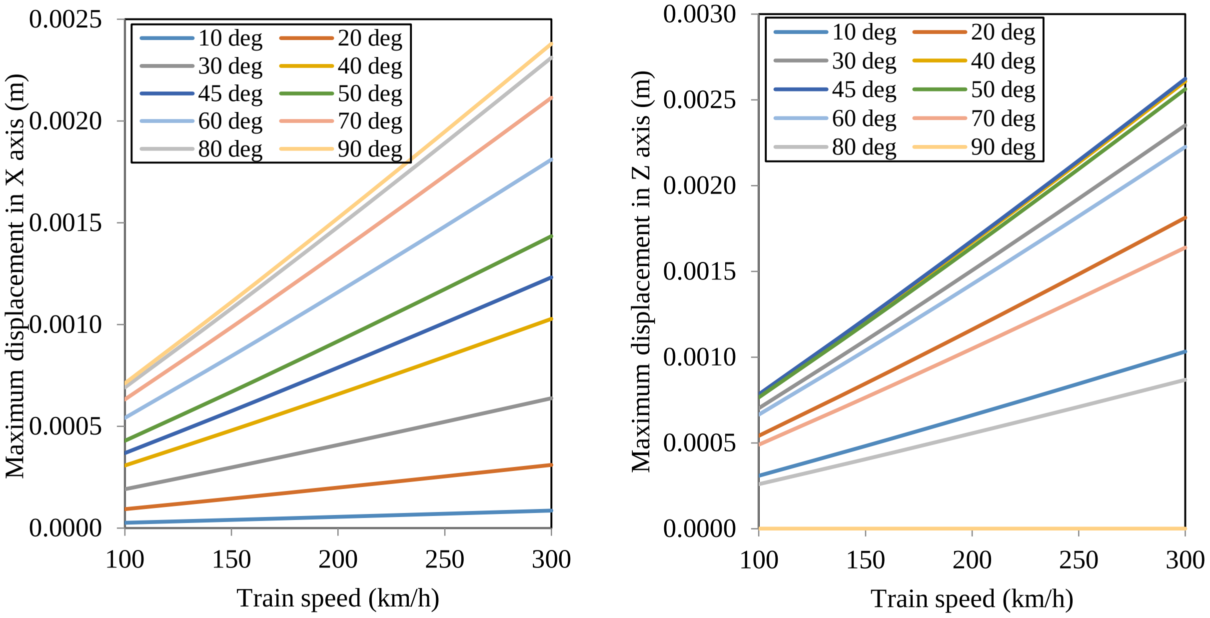


c) d)

e) f)

Figure 5 Maximum displacement at the position of overhead wire on cantilever mast at various angles and soil stiffness a) 100km/h in X (transverse) direction b) 100km/h in Z (longitudinal) direction c) 200km/h in X (transverse) direction d) 200km/h in Z (longitudinal) direction e) 300km/h in X (transverse) direction f) 300km/h in Z (longitudinal) direction.

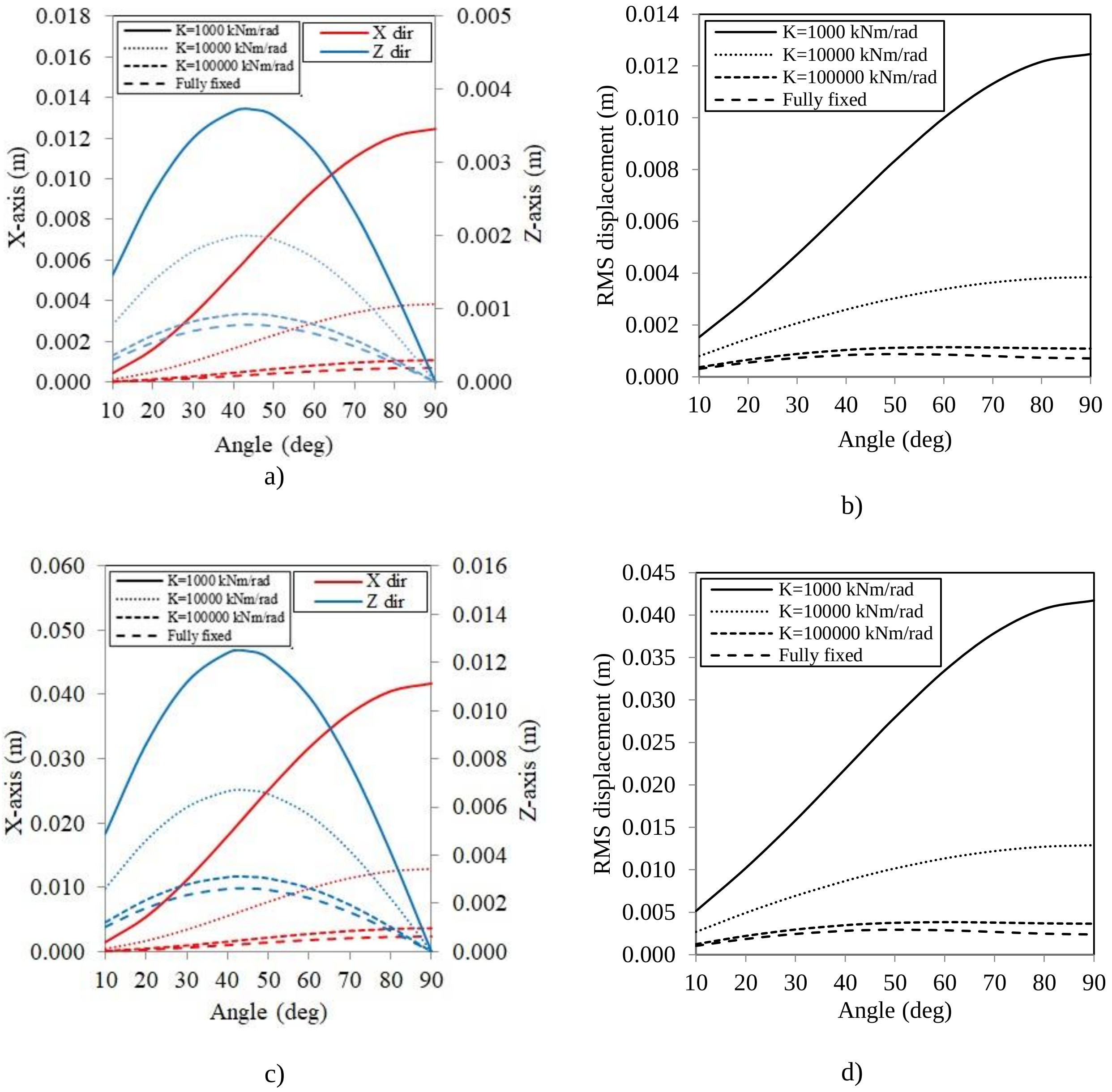
At fully fixed support condition or rigid soil, it is clearly seen that the train speed plays a little role on transverse direction when angles of the train to the mast are in low range (less than 30 degrees) but plays a significant role at higher angles, as shown in Figure 6. For 70-90 degrees, it should be noted that the maximum displacement in transverse direction increases nearly double and triple from the speed of 100km/h to 200km/h and 300km/h, respectively. Whereas, for 40-60 degrees, there are nearly two fold increases in maximum displacement from 100km/h to 300km/h. In Figure 6b, with longitudinal direction, the angles which create the highest displacement are between 40 and 50 degrees. This is because the highest vibration velocities occur when the train runs past these angles as seen in Figure 4. The maximum displacements are nearly two and three fold increases from 100km/h to 300km/h for the angles of 30-60 degrees.



a) b)

Figure 6 Maximum displacement of mast at various train speeds and angles with fully fixed support condition in a) X (transverse) direction b) Z (longitudinal) direction

Figure 7 shows the trends of maximum displacement in both direction and root mean square displacement corresponding to different angles. As for root mean square (RMS) displacement, the results indicate that the RMS displacement trend has a rapid increase when the train runs to and angle of 80 degree and then stays constant until the train passes the mast with the soil stiffness of 1000kNm/rad. In case of higher stiffness, it is clear that the RMS displacements remain steady after the train forms the angle of 40 degree due to the twisting mode. However, the displacement concerned in the loss of contact wire is in transverse direction. It should be noted that the 50mm construction tolerances of contact stagger is considered as allowable movement in transverse direction (Railcorp, 2011). It is noted that about 40mm is observed as the maximum displacement in transverse direction when the trains run past the mast at the stiffness of 1000kNm/rad with the speed of 300km/h. It can be concluded that the high speed train cannot cause the damage of contact wire which lead to the failure of electric system.



a)

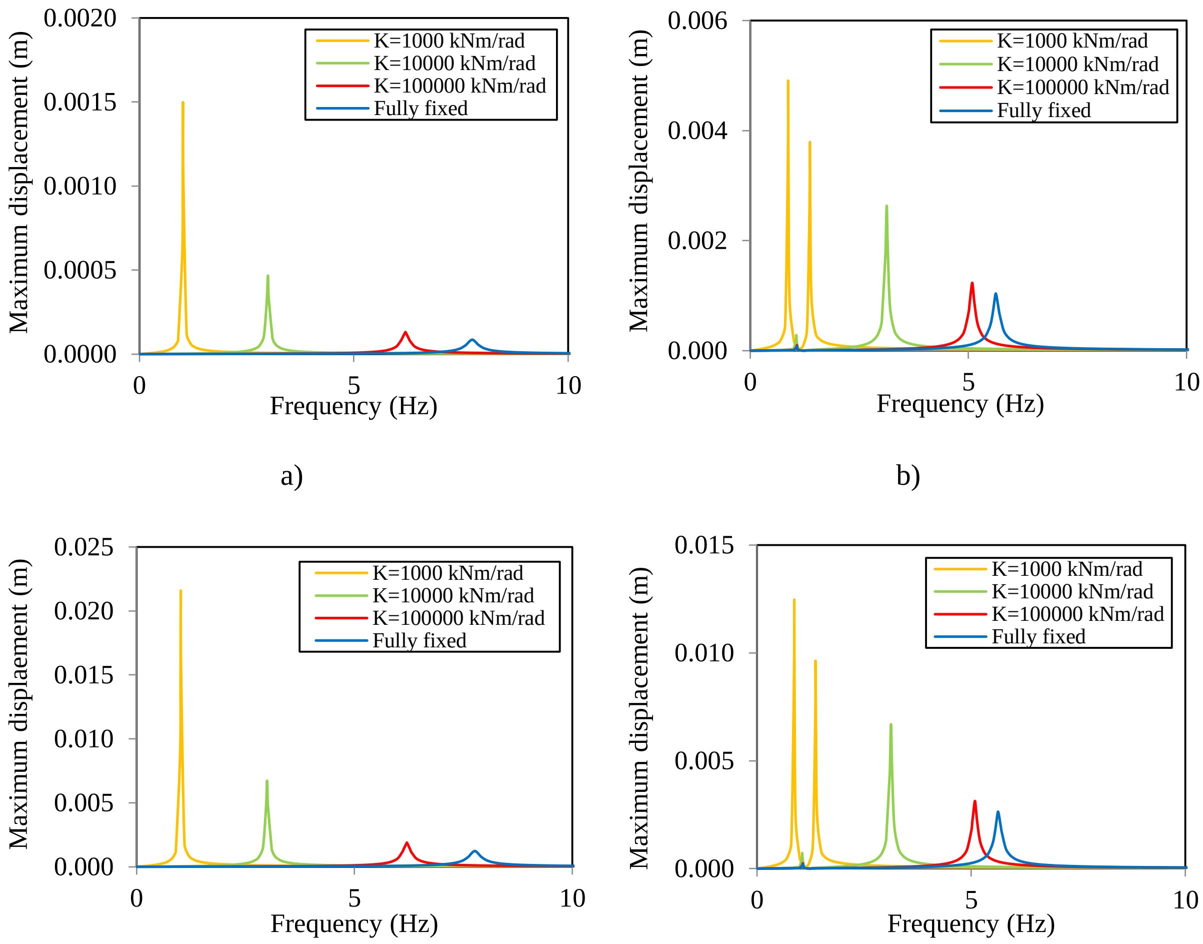
b)

c)

d)

Figure 7 Maximum displacement of mast at velocity of 100km/h in a) X (transverse) and Z (longitudinal) directions b) Root mean square 300km/h in c) X (transverse) and Z (longitudinal) directions d) Root mean square

Figure 8 shows the frequency response of the maximum displacement in both directions. It can be seen that the fundamental frequencies change due to the change of soil stiffness beneath the mast structure. When the soil stiffness decreases, the dominant frequencies are reduced with a higher magnitude of displacement responses. The resonance phenomenon occurs when the frequencies of ground borne vibration related to the frequencies of the structure are generated. This can be observed due to the occurrence of large displacement. It is clearly seen that the dynamic behaviour of the mast structure, as mentioned (Ngamkhanong et al., 2017), is relevant to the dominant frequencies, as shown in Figure 8. It is interesting to note that there are two peaks of displacement observed when the mast has a poor support with a stiffness of 1000kNm/rad. Because of the sensitivity of dynamic behaviour, the structure vibrates with a combination of twisting and bending about the X-axis and pure bending about the X-axis so that the two peaks are seen. There is only peak observed in the other cases of stiffness.



a)

b)

c) d)

Figure 8 Frequency response of the maximum displacement with the train speed of 300km/h at the angle of a) 10 degrees in X (transverse) direction b) 10 degrees in Z (longitudinal) direction c) 45 degrees in X (transverse) direction d) 45 degrees in Z (longitudinal) direction

Figures 9a-9b show the rotation of cantilever mast around the mast column with varying angles and soil stiffness at the frequencies of 1.07Hz and 0.87Hz. It should be noted that the fundamental mode of twisting for mast structure with rotational stiffness higher than 10000kNm/rad and 1000kNm/rad are 1.07Hz and 0.87Hz, respectively. It is clearly seen that stiffness plays a significant role the mode of vibration. Even though the resonance effect occurs on the mast with a stiffness of higher than 100000kNm/rad, when the ground vibrates at a frequency of around 1.07Hz, the rotations of the cantilever observed are very small because of the well or rigid support conditions. The maximum rotation can be observed when the train runs past the angle of 45 degrees and leads to the rotation of mast at 10000kNm/rad soil stiffness. On the other hand, when the train induces ground vibration with a frequency of 0.87Hz, the maximum response occurs with the mast structure with the poor support condition. It is interesting to note that there is a more than tenfold higher rotation of the cantilever of the mast because of the occurrence of the resonance effect. It should be noted that the resonance vibration on the mast structure with the lower soil stiffness is higher than that with higher soil stiffness.

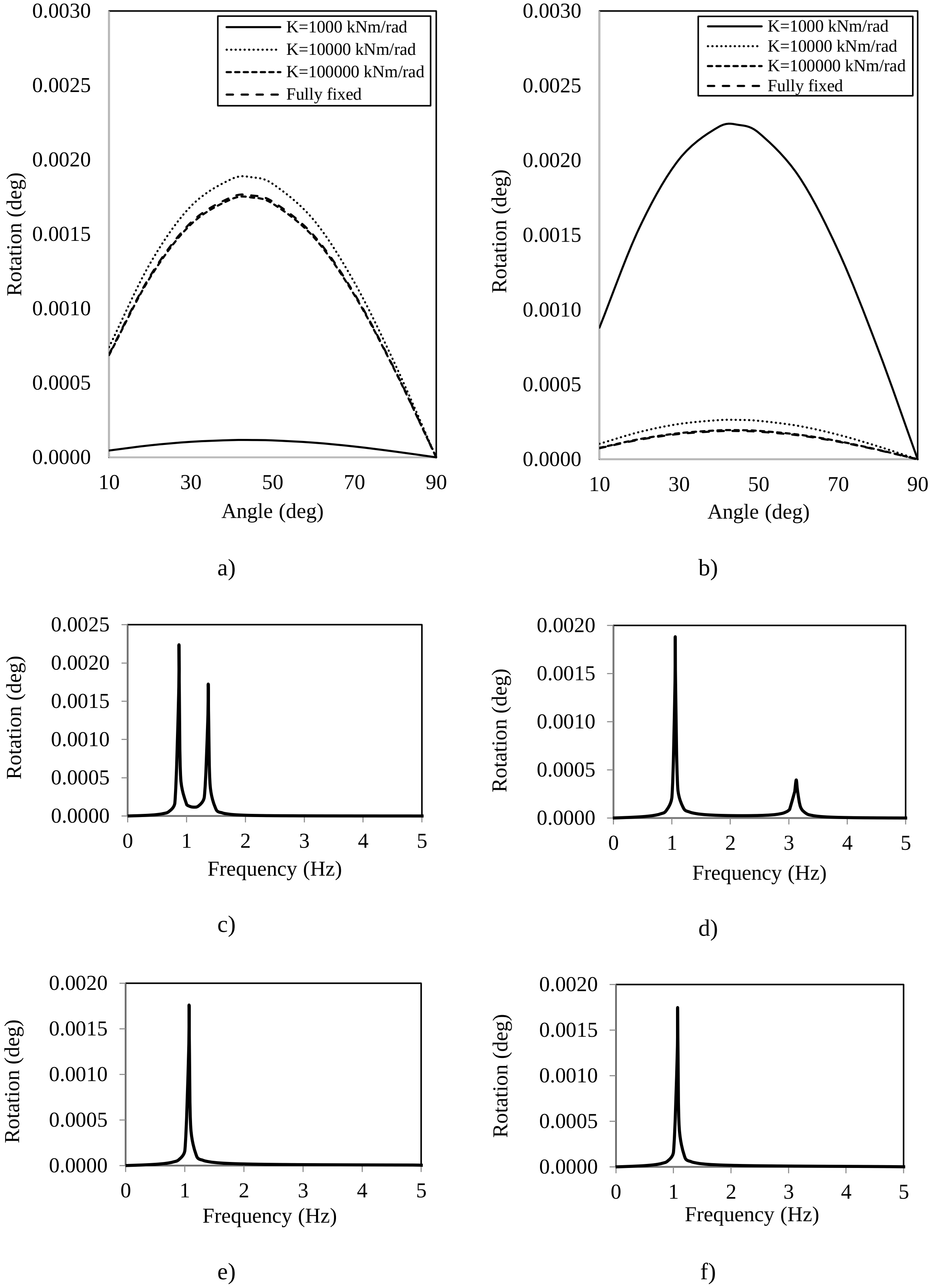


Figure 9 Cantilever rotation at train speed of 300km/h around Y axis at the frequency of a) 1.07Hz b) 0.87Hz and frequency response of the rotation of cantilever mast with soil stiffness of c) 1000kNm/rad d) 10000kNm/rad e) 100000kNm/rad f) fully fixed support

Figures 9c-9f show the frequency responses in the rotation of cantilever mast around the mast column with different soil stiffness. The two peaks of rotation are observed at a stiffness of 1000kNm/rad and 10000kNm/rad due to the poor dynamic behaviour. The second highest peak of these cases takes place in the second mode of vibration which is bending about the X-axis. Since the mast structure becomes weak due to the reduction of soil stiffness below, the first mode of bending about the X-axis is combined with twisting. It can be concluded that the soil stiffness plays a vital role in the vibration responses of the structure due to ground-borne vibrations.

4. Conclusions

The rapid growth in railway infrastructure demand has meant an increase in the capacity of trains is necessary. Ground borne vibration intensity has increased due to the increase in train speed, and other factors related to vibration source, vibration path and receiver. The mast structure located alongside the railway track is a support for overhead line equipment (OHLE) to supply the electric power to the train. In practical work, the structures are designed with the assumption of having fixed support. In reality, there is a small displacement created by the supporting soil. Hence, a three-dimensional mast structure is created using a finite element package, STRAND7, with the consideration of soil-structure interaction. The obtained results show that the resonance effect occurs and will amplify the effects of a ground motion, causing a structure to suffer more oscillation. It is also noticed that the vibration responses are dominant at the train location near the mast structure, whereas the response decreases rapidly with the increasing distance. The largest displacement occurs when the train moves past the mast structure at the track perpendicular to the structure. It is also observed that the first twisting mode can occur when the train is run past the 45 degrees from cantilever mast. The soil stiffness beneath the structure also plays a role in the reduction of resonance phenomenon. Nonetheless, there are some limitations in this study. The ground borne vibrations are formulated by the prediction model with only one frequency, whereas the ground vibration velocity has more than one dominant frequency in reality. Therefore, there should be more than one resonance frequency. It is also recommended that there should be further field measurement. However, the results obtained can be used as tolerances for the consideration of further design standard before the effect of extreme events will be considered. The outcome of this study will help provide a better understanding of the critical responses and behaviour of mast structure under normal operation of high speed train. It is the first investigate to demonstrate the effect of ground borne vibration generated by high speed train on the cantilever mast structure and contact wire system.

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