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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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1    **The effect of ground borne vibrations from high speed train on overhead line equipment**

2    **(OHLE) structure considering soil-structure interaction**

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11

12   **Abstract:** At present, railway infrastructure experiences harsh environments and aggressive loading

13   conditions from increased traffic and load demands. Ground borne vibration has become one of these

14   environmental challenges. Overhead line equipment (OHLE) provides electric power to the train and

15   is, for one or two tracks, normally supported by cantilever masts. A cantilever mast, which is made of

16   H-section steel, is slender and has a poor dynamic behaviour by nature. It can be seen from the literature

17   that ground borne vibrations cause annoyance to people in surrounding areas especially in buildings.

18   Nonetheless, mast structures, which are located nearest and alongside the railway track, have not been

19   fully studied in terms of their dynamic behaviour.  This paper presents the effects of ground borne

20   vibrations generated by high speed trains on cantilever masts and contact wire located alongside railway

21   tracks. Ground borne vibration velocities at various train speeds, from 100 km/h to 300km/h, are

22   considered based on the consideration of semi-empirical models for predicting low frequency vibration

23   on ground. A three-dimensional mast structure with varying soil stiffness is made using a finite element

24   model. The displacement measured is located at the end of cantilever mast which is the position of

25   contact wire. The construction tolerance of contact stagger is used as an allowable movement of contact

26   wire in transverse direction. The results show that the effect of vibration velocity from train on the

27  transverse direction of mast structure is greater than that on the longitudinal direction. Moreover, the

28  results obtained indicate that the ground bourn vibrations caused by high speed train are not strong

29  enough to cause damage to the contact wire. The outcome of this study will help engineers improve the

30  design standard of cantilever mast considering the effect of ground borne vibration as preliminary

31  parameter for construction tolerances.

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

33  interaction

34  **1. Introduction**

35  Presently, due to rapid population growth, passenger journeys have increased by nearly 100% and

36  freight by 60% (Baxter, 2015). The extra capacity provided is needed for economic growth in the future

37  (RailCorp, 2011).  The electric train has become the efficient railway systems. The electric train is

38  allowed to run frequently and quickly. Overhead line equipment (also called "OHLE") is an equipment

39  to supply power to make electric trains and consist of masts, gantries, and wires found along electrified

40  railways.  This is now the preferred means of powering trains throughout the world. Although the

41  concept of OHLE is simple, the problem is the poor dynamic behaviour of OHLE (Beagles et al., 2016).

42  Due to the extreme environmental events and severe periodic forces, such as earthquakes in surrounding

43  areas perhaps causing damage to the track and OHLE structure especially the mast structure, this can

44  lead to the failure of the electrical system (Shing and Wong, 2008; Robinson and Bryan, 2009; Taylor,

45  2013). This is because when the frequency of ground motion matches the natural frequency of a

46  structure, it will suffer the damage and large oscillations because of the occurrence of resonance effect

47  (Ngamkhanong and Pinkaew, 2015). Apart from earthquake, ground borne vibration is a serious

48  concern. One of the main sources of ground borne vibration on mast structures is trains passing. Railway

49  vibration is a serious global concern as it can affect property and cause annoyance to people in

50  surrounding area (Connolly et al., 2016). The vibration level depends on many factors such as train

51  speed, ground condition, type of structure concerned etc. The effect of ground borne vibration on the

52  building in surrounding areas has been studied in previous literature (Kouroussis et al., 2013; Zou et

53    al., 2015; Zou et al., 2017; Vogiatzis and Mouzakis, 2017). Even though the ground borne vibration

54    might not cause damage to the structure, this may cause annoyance to the people in the building

55    (Suhairy, 2000; Lopes et al., 2016). Cantilever mast structures have not been fully studied. In practice,

56    masts are designed as a fixed support with infinite stiffness. In reality, there is a small displacement

57    created by the supporting soil. Based on the relevant literature (Prum and Jiravacharadet, 2012; NEHRP,

58    2012), different soil support conditions were taken into account. It was noted that soil-structure

59    interaction affected the overall response of the structure. As for mast structure, it was noticeable that

60    the rotational stiffness affected the natural frequencies and mode shape of vibration in a lower mode

61    but rarely affected the higher mode (Ngamkhanong et al., 2017). This was because the dynamic

62    behaviour was characterized by coincident eigenfrequencies, mode order change, while the

63    eigenfunctions remain associated with the corresponding eigenvalues (Pierre, 1988; Benedettini et al.,

64    2009; Sari et al., 2017). For most railway vibration problems, the predominant frequencies of the load

65    spectra are normally in the range of 0.5Hz to 80Hz (Jonsson, 2000) depending on wheel-rail

66    irregularities and vehicle effects (Kouroussis et al., 2014; Kouroussis et al., 2015). Therefore, this study

67    considers the frequencies of ground borne vibration between 0Hz and 100Hz to cover all possible

68    frequencies of ground vibration and the first-eight fundamental mode of mast vibration.

69    The present paper aims to study the effect of ground borne vibration generated by high speed trains on

70    mast structures, with consideration of its underlying soil properties. Finite element model is employed

71    to calculate the structural responses and the ground borne vibration is computed by the classical

72    formulation based on the semi-empirical model for predicting low frequency vibration on soft ground

73    condition (Kurzeil, 1979; Madshus et al., 1996). The obtained simulation results reveal that the train

74    speed and soil condition influence the dynamic responses of mast structure.

75    **2.  Methodology**

76    **2.1 Modelling**

77    In this study, the 3-dimensional finite element modelling is considered using a general-purpose finite

78    element package STRAND7 (G+D Computing, 2001). OHLE is normally supported by lineside masts,

79  typically made of H-section steel, with a fixed base. The catenary cable and the pull/push-off arms

80  supporting the contact wire are attached to the ends of the cantilever. The modelling of cantilever mast

81  structure is shown in figure 1, which consists of the two force members only. The young modulus of

82  steel is $2x10^5$ MPa with a density of 7850 kg/m$^3$. Poisson's ratio is 0.25.
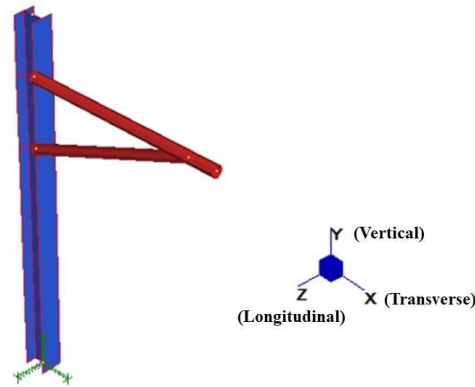


83

84  **Figure 1** 3-Dimensional model of OHLE

85  In this study, the translational stiffness in three directions is assumed to be fixed in order to restraint the

86  translation displacement. Based on soil conditions, however, translational stiffness is not taken into

87  account, and rotational stiffness of support conditions is varied from 1000kNm/rad to infinite (fully

88  fixed support).

89  **2.2 Ground borne vibration**

90  Based on vibration measurements, it has been concluded that the factors that are of primary importance

91  for the low frequency railway-induced vibration on the ground, and its effect in surrounding areas are

92  as follows (Madshus et al., 1996): (1) Ground conditions, (2) Train type, (3) Line quality and

93  embankment design, (4) Train speed, (5) Distance from track to structure, and (6) Building foundation

94  and structure.

95  To conveniently calculate the level of ground borne vibration, the formula proposed by Madshus et al.

96  (1996) can be used, as shown in Eq.1.

97
$$V = V_T F_s F_D F_R F_B \qquad (1)$$

98    Where

99    $V_T$ 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

100   factor and $F_B$ is a building amplification factor.

101   $F_s$ can be calculated as shown in Eq.2 where $A$ is the train speed exponent, $S$ is the train speed and $S_0$

102   is the reference speed on a standard track.

103
$$F_s = \left(\frac{S}{S_0}\right)^A \qquad (2)$$

104   Distance factor, $F_D$, can be calculated as shown in Eq.3 where $D$ is the distance from the centre of the

105   track to the receiver, $D_0$ is the reference distance from the centre of the tracks and $B$ is the distance

106   exponent.

107
$$F_D = \left(\frac{D}{D_0}\right)^{-B} \qquad (3)$$

108   The low frequency vibration peak can be observed dominantly in the softer ground (Madshus et al.,

109   1996; Auersch, 2012) and thus it is assumed that high speed trains run along the track on soft ground.

110   Therefore, the values used for ground vibration calculation are 0.1, 0.9 and 1.1 for $V_T$, $A$ and $B$. In

111   addition, vibration level on the ground at a reference distance of $D_0 = 20$m, from the centre of the

112   tracks, when a train of the specified category passes at reference speed of $S_0 = 70$ km/h. It should be

113   noted that the excessive vibration and degradation of surrounding soil can be detected at soft soil areas

114   during high-speed train passage (Madshus and Kaynia, 2000; Vogiatzis, 2012)

115   The typical ($F_R$) used is 1.3 for old single track and structure amplification ($F_B$) is 1.3 for single storey

116   buildings which are the best fit for single mast structure based on the height of structure. According to

117   previous measurement on building (Mouzakis and Vogiatzis, 2016), it was interesting to note that the

118   amplification factor indicated the increase in vibration up to 25Hz which covered the fundamental mode

119   of vibration of mast structure.

120   It is assumed that the mast structure is located at a distance of 3.5m perpendicular to the track. The train

121   speed varies from 100km/h to 300km/h. The ground vibration velocities created by train are inputted in

122   both directions as seen in Figure 2. When the train moves on the track, the ground vibration has

123   intensities depending on the distance or angle formed by track and distance from a train to the mast

124   structure. The vibration is transmitted as Rayleigh surface waves in the propagation region to the

125   structure. In this study, the different angles that create different distances from mast are considered as

126   a vibration creation regions.
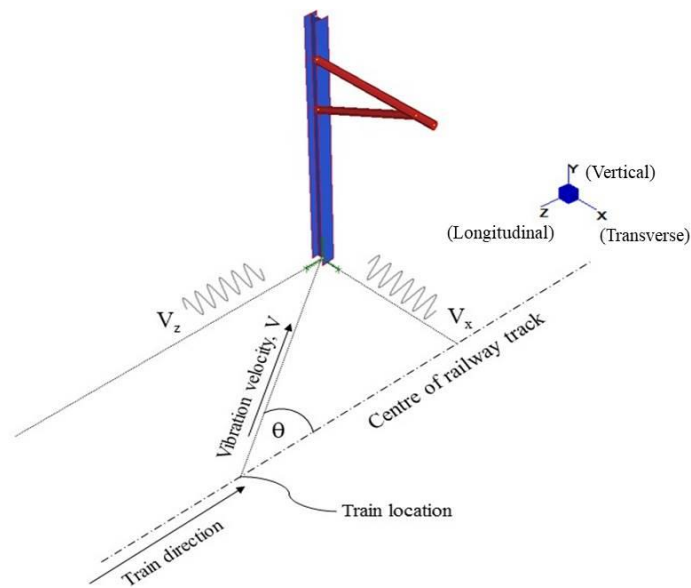


127

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

129   The relationships between vibration velocity and train speed between 0km/h and 300km/h at the angle

130   of 10 and 90 degrees are shown in Figure 3. As for 10 degrees, it can be seen that the vibration velocity

131   in longitudinal direction is greater than that in transverse direction. Meanwhile, only vibrations in

132   transverse direction can be observed when the train is located perpendicular to the track. The 3mm/s

133   displacement in transverse direction can be observed at the train speed of 300km/h. It should be noted

134   that the frequency ranges from 1 to 100Hz are considered in this study to cover the fundamental mode

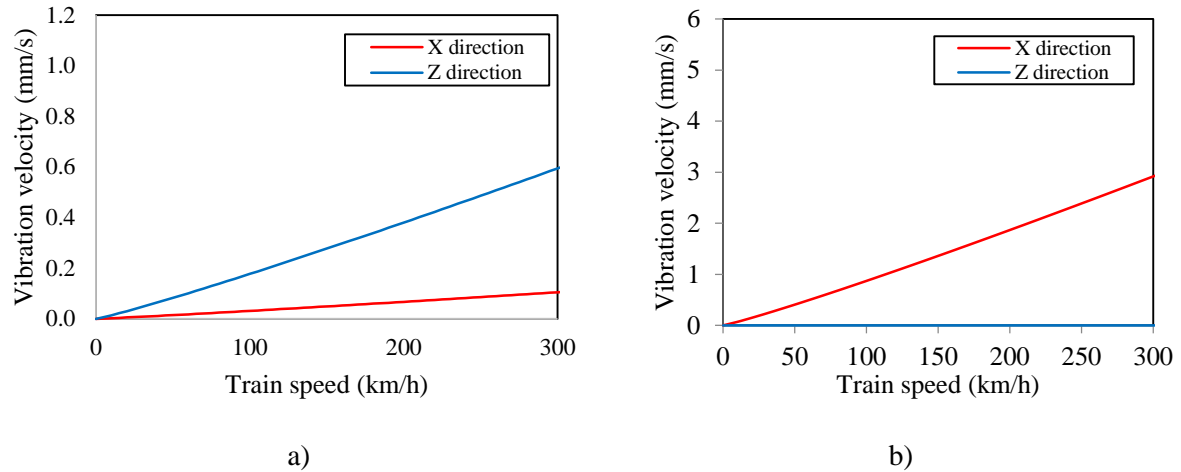135   of vibration of the mast structure.

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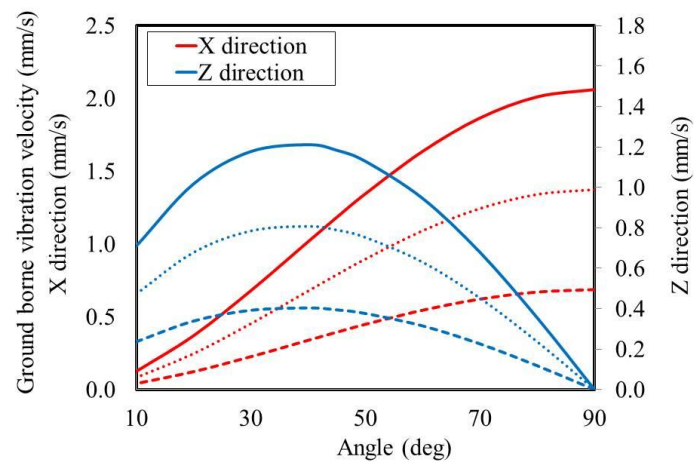
148 **Figure 4** Ground borne vibration velocity at various distances from the track at a speed of 100km/h,

149 200km/h and 300km/h.

150 3. **Results and Discussion**

151 In this study, the frequency ranges between 1 and 100Hz are considered to cover the fundamental mode

152 shapes of the mast structure. Based on previous study (Ngamkhanong et al., 2017), the first, second and

153 third modes are twisting, bending about transverse, and bending about longitudinal, respectively. It was

154 noted that the reduction of soil-structure stiffness associated with poor support and soft soil condition

155 led to the decrease in natural frequency and the change of mode shapes in lower modes.

156 Figure 5 shows maximum displacement at the end of the cantilever mast, which is the location of

157 overhead wire, in both directions at various soil stiffness. It can be seen that, for higher stiffness from

158 about 100000kNm/rad to infinity, the displacements are very small compared with the lower stiffness.

159 As expected, when the mast is located on the very poor support condition corresponding to the stiffness

160 of 1000kNm/rad, the displacement is more than 5 times higher than that of the well support. In Figures

161 5a, 5c, 5e, it is clearly seen that when the train runs along the track, it can make ground vibrations and

162 leads to the movement of mast especially in the perpendicular direction to the track. At the stiffness of

163 1000kNm/rad, about 40mm displacement can be observed when the train speed of 300km/h passes the

164 mast at an angle of 90 degrees.


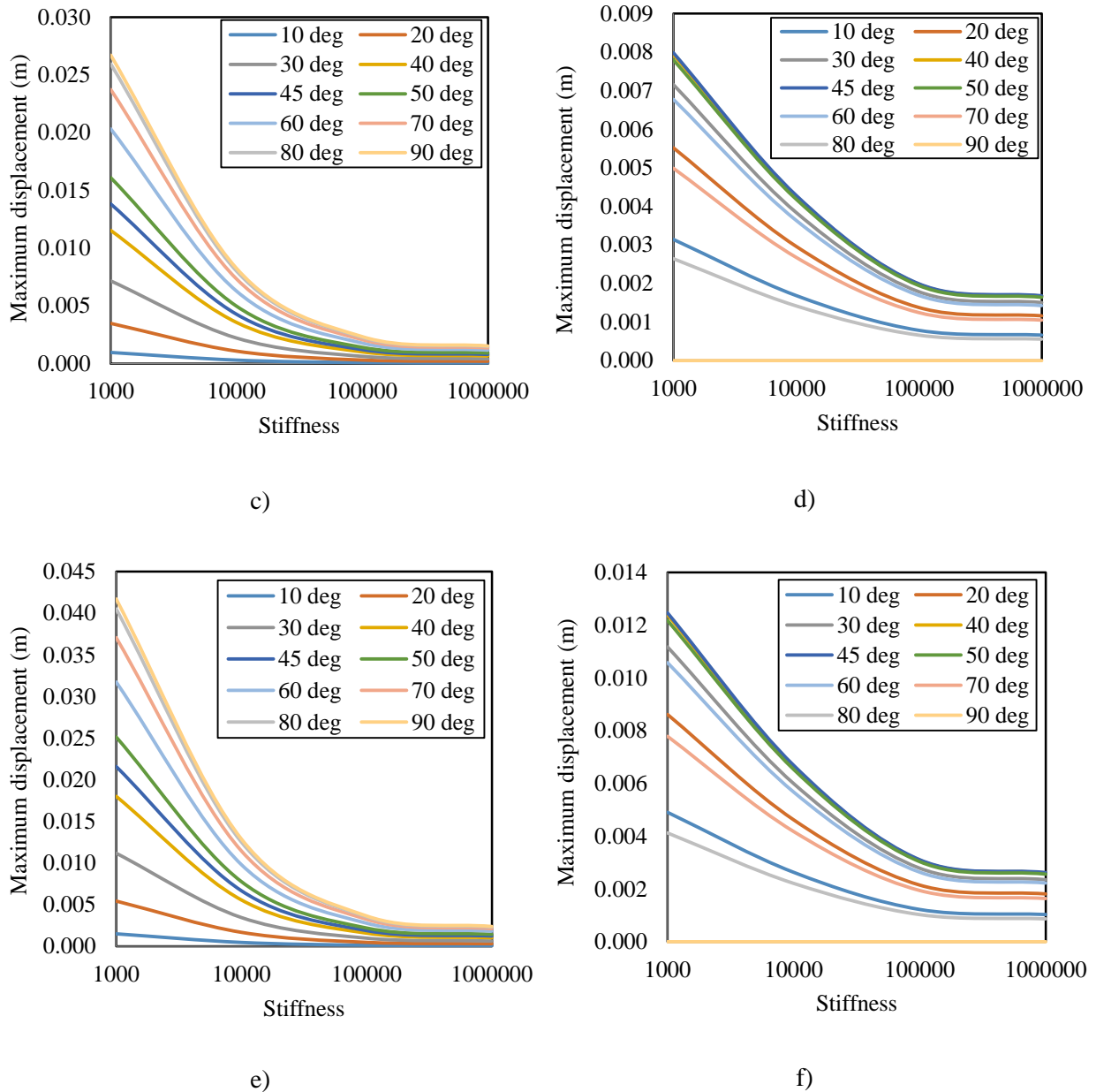
a)

b)

c)

d)



e)

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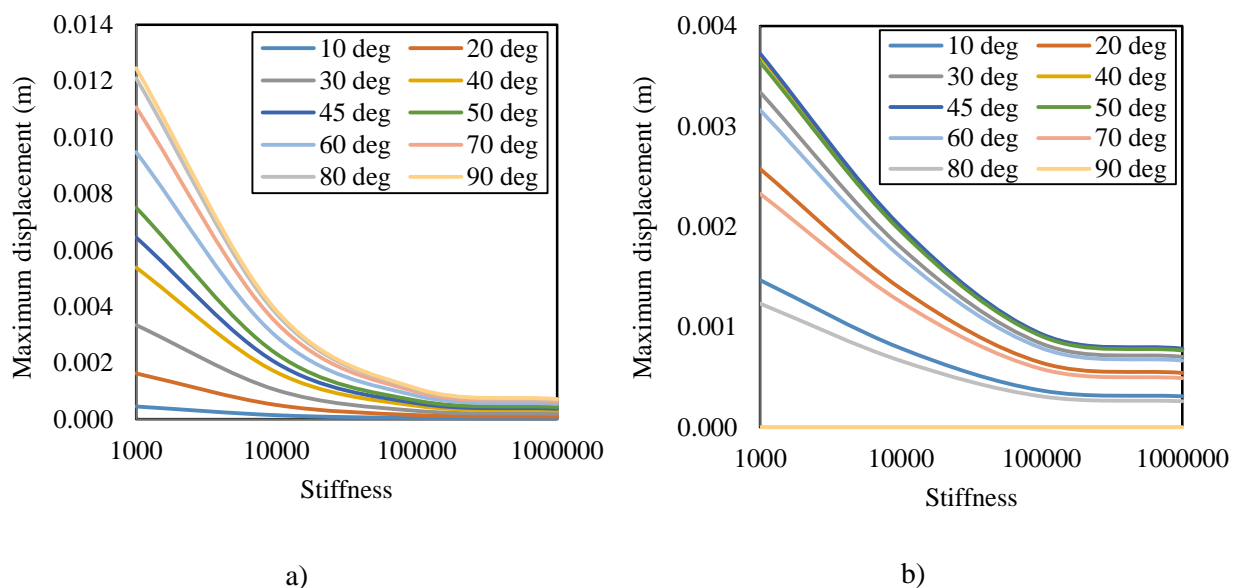
**Figure 5** Maximum displacement at the position of overhead wire on cantilever mast at various angles and soil stiffness a) 100km/h in X (transverse) direction b) 100km/h in Z (longitudinal) direction c) 200km/h in X (transverse) direction d) 200km/h in Z (longitudinal) direction e) 300km/h in X (transverse)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

173  of 100km/h to 200km/h and 300km/h, respectively. Whereas, for 40-60 degrees, there are nearly two

174  fold increases in maximum displacement from 100km/h to 300km/h. In Figure 6b, with longitudinal

175  direction, the angles which create the highest displacement are between 40 and 50 degrees. This is

176  because the highest vibration velocities occur when the train runs past these angles as seen in Figure 4.

177  The maximum displacements are nearly two and three fold increases from 100km/h to 300km/h for the

178  angles of 30-60 degrees.



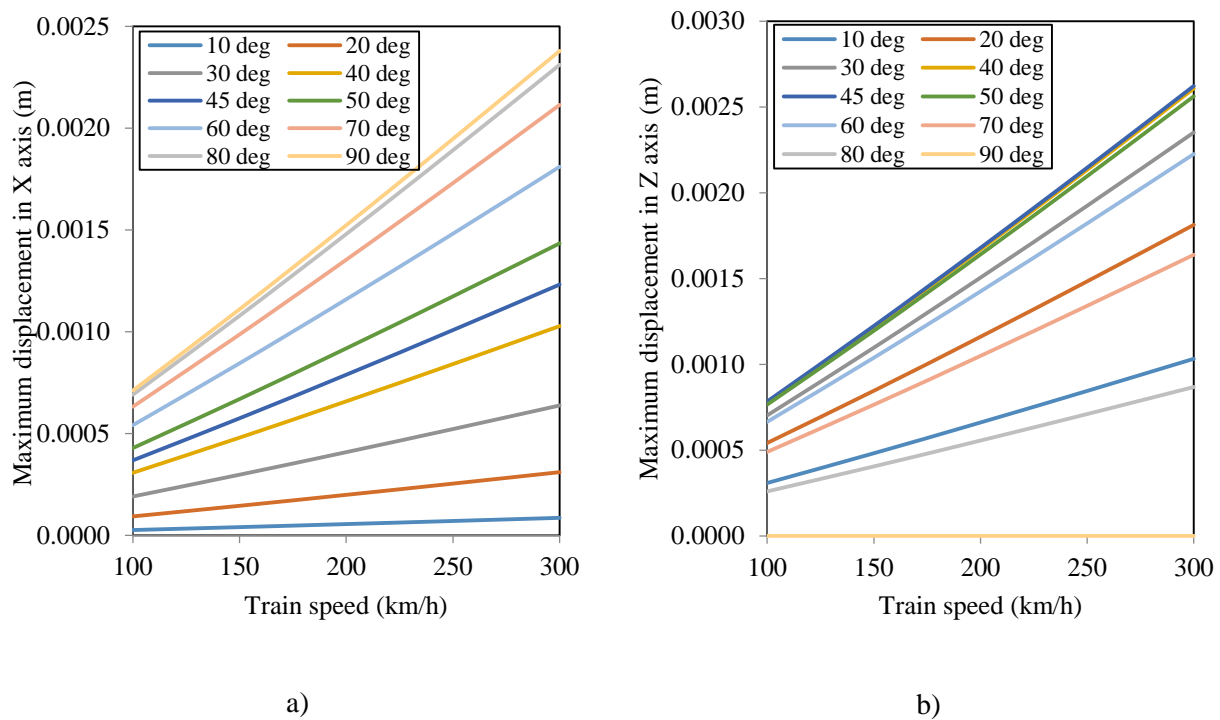a)                                                                                  b)

179     **Figure 6** Maximum displacement of mast at various train speeds and angles with fully fixed support

180                            condition in a) X (transverse) direction b) Z (longitudinal) direction

181  Figure 7 shows the trends of maximum displacement in both direction and root mean square

182  displacement corresponding to different angles. As for root mean square (RMS) displacement, the

183  results indicate that the RMS displacement trend has a rapid increase when the train runs to and angle

184  of 80 degree and then stays constant until the train passes the mast with the soil stiffness of

185  1000kNm/rad. In case of higher stiffness, it is clear that the RMS displacements remain steady after the

186  train forms the angle of 40 degree due to the twisting mode. However, the displacement concerned in

187  the loss of contact wire is in transverse direction. It should be noted that the 50mm construction

188  tolerances of contact stagger is considered as allowable movement in transverse direction (Railcorp,

189    2011). It is noted that about 40mm is observed as the maximum displacement in transverse direction

190    when the trains run past the mast at the stiffness of 1000kNm/rad with the speed of 300km/h. It can be

191    concluded that the high speed train cannot cause the damage of contact wire which lead to the failure

192    of electric system.

193



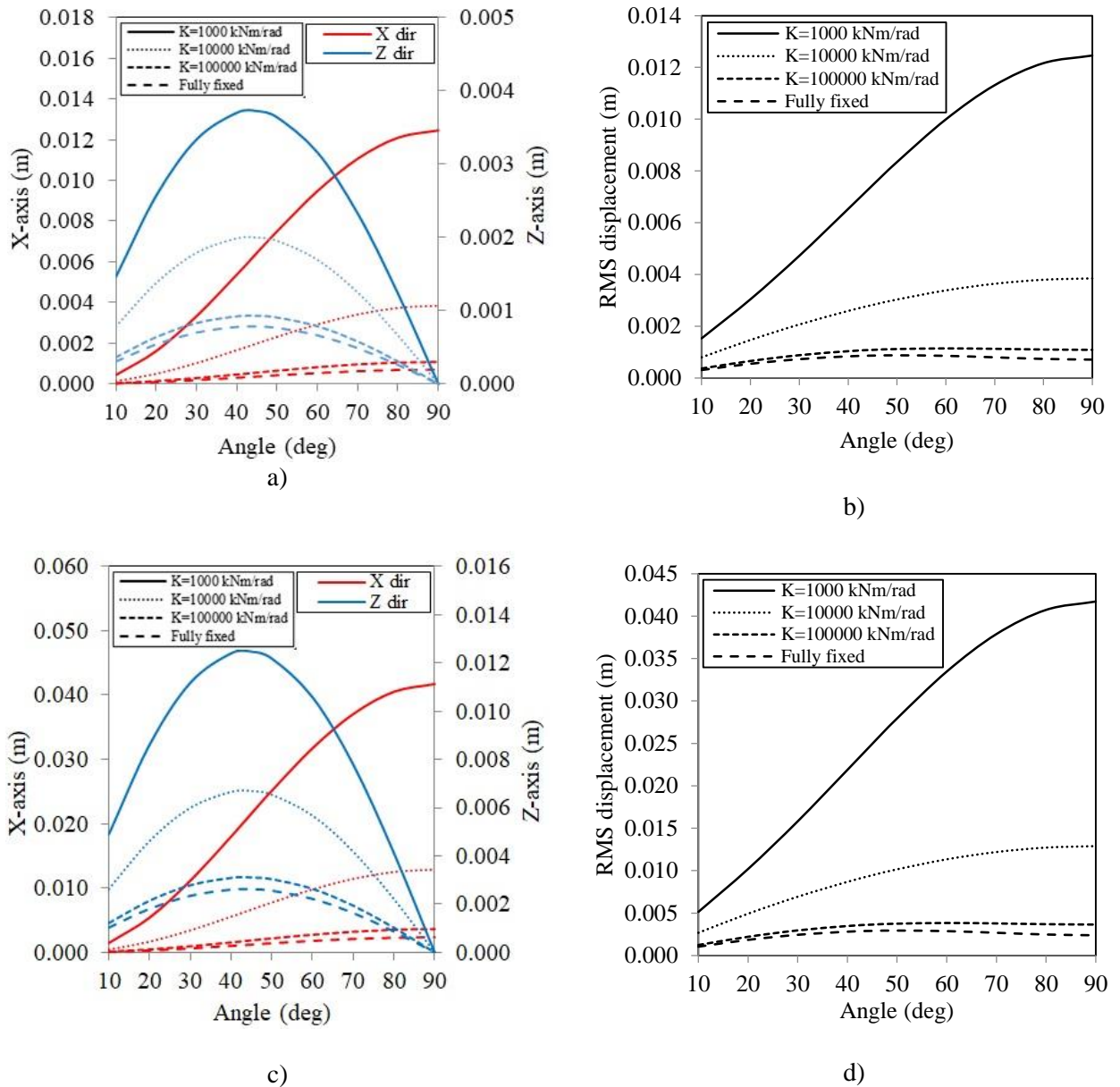194                **Figure 7** Maximum displacement of mast at velocity of

195            100km/h in a) X (transverse) and Z (longitudinal) directions b) Root mean square

196            300km/h in c) X (transverse) and Z (longitudinal) directions d) Root mean square

197     Figure 8 shows the frequency response of the maximum displacement in both directions. It can be seen

198     that the fundamental frequencies change due to the change of soil stiffness beneath the mast structure.

199     When the soil stiffness decreases, the dominant frequencies are reduced with a higher magnitude of

200     displacement responses. The resonance phenomenon occurs when the frequencies of ground borne

201     vibration related to the frequencies of the structure are generated. This can be observed due to the

202     occurrence of large displacement. It is clearly seen that the dynamic behaviour of the mast structure, as

203     mentioned (Ngamkhanong et al., 2017), is relevant to the dominant frequencies, as shown in Figure 8.

204     It is interesting to note that there are two peaks of displacement observed when the mast has a poor

205     support with a stiffness of 1000kNm/rad. Because of the sensitivity of dynamic behaviour, the structure

206     vibrates with a combination of twisting and bending about the X-axis and pure bending about the X-

207     axis so that the two peaks are seen. There is only peak observed in the other cases of stiffness.

208



a)



b)

c)                                                    d)
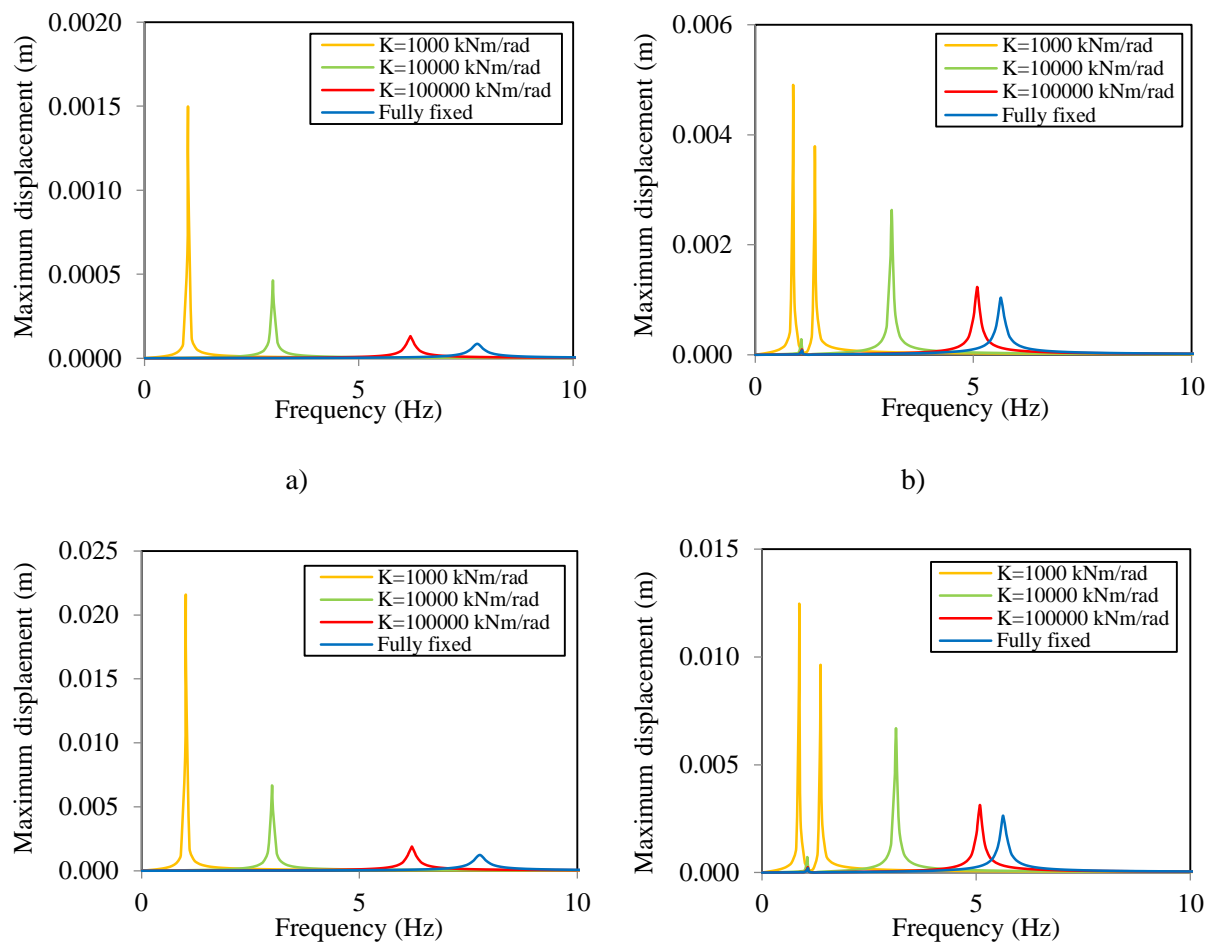
209    **Figure 8** Frequency response of the maximum displacement with the train speed of 300km/h at the

210        angle of a) 10 degrees in X (transverse) direction b) 10 degrees in Z (longitudinal) direction

211            c) 45 degrees in X (transverse) direction d) 45 degrees in Z (longitudinal) direction

212    Figures 9a-9b show the rotation of cantilever mast around the mast column with varying angles and soil

213    stiffness at the frequencies of 1.07Hz and 0.87Hz. It should be noted that the fundamental mode of

214    twisting for mast structure with rotational stiffness higher than 10000kNm/rad and 1000kNm/rad are

215    1.07Hz and 0.87Hz, respectively. It is clearly seen that stiffness plays a significant role the mode of

216    vibration. Even though the resonance effect occurs on the mast with a stiffness of higher than

217    100000kNm/rad, when the ground vibrates at a frequency of around 1.07Hz, the rotations of the

218    cantilever observed are very small because of the well or rigid support conditions. The maximum

219    rotation can be observed when the train runs past the angle of 45 degrees and leads to the rotation of

220    mast at 10000kNm/rad soil stiffness. On the other hand, when the train induces ground vibration with

221    a frequency of 0.87Hz, the maximum response occurs with the mast structure with the poor support

222    condition. It is interesting to note that there is a more than tenfold higher rotation of the cantilever of

223    the mast because of the occurrence of the resonance effect. It should be noted that the resonance

224    vibration on the mast structure with the lower soil stiffness is higher than that with higher soil stiffness.
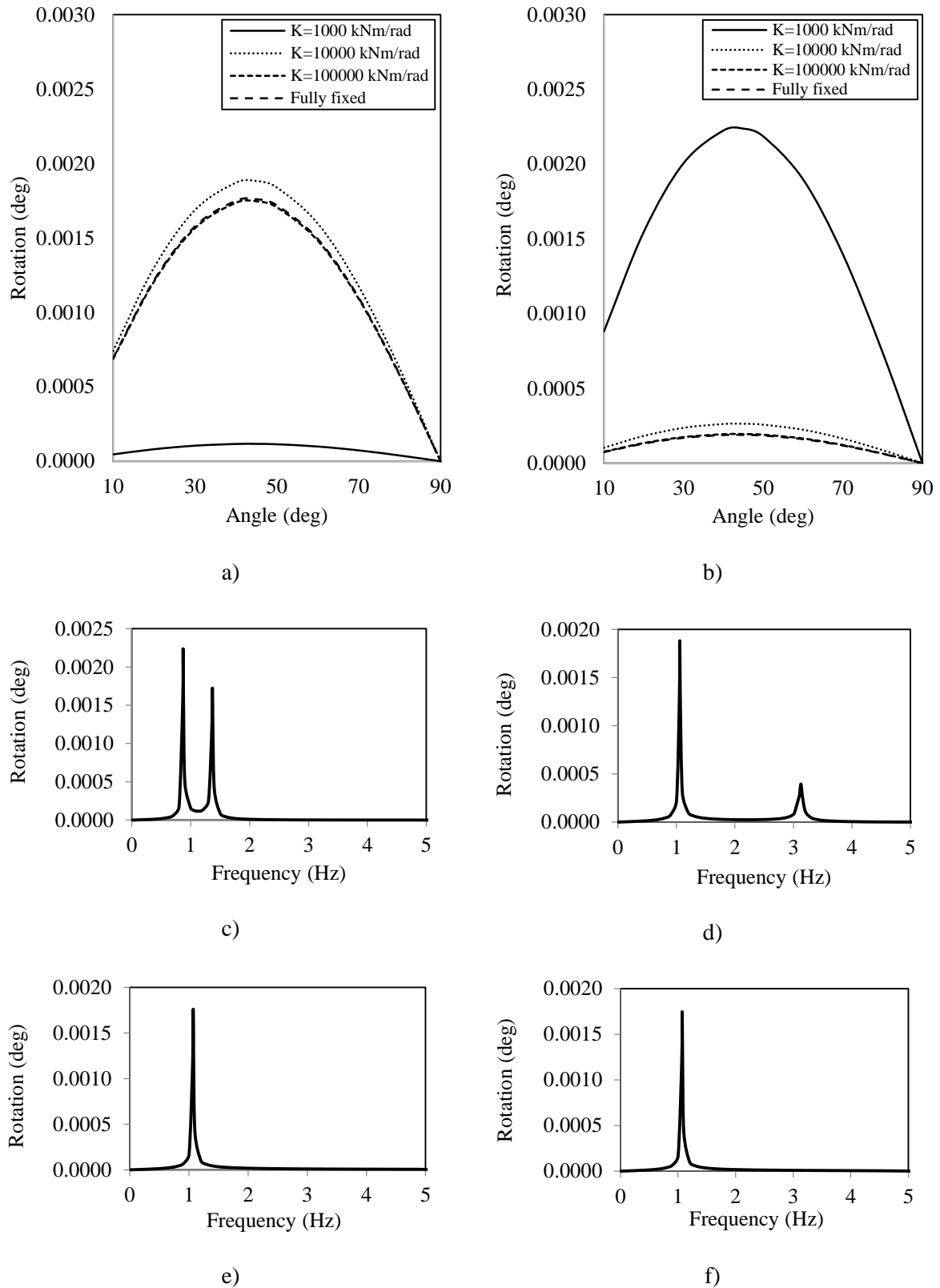
**Figure 9** Cantilever rotation at train speed of 300km/h around Y axis at the frequency of a) 1.07Hz b) 0.87Hz and frequency response of the rotation of cantilever mast with soil stiffness of c) 1000kNm/rad d) 10000kNm/rad e) 100000kNm/rad f) fully fixed support

228    Figures 9c-9f show the frequency responses in the rotation of cantilever mast around the mast column

229    with different soil stiffness. The two peaks of rotation are observed at a stiffness of 1000kNm/rad and

230    10000kNm/rad due to the poor dynamic behaviour. The second highest peak of these cases takes place

231    in the second mode of vibration which is bending about the X-axis. Since the mast structure becomes

232    weak due to the reduction of soil stiffness below, the first mode of bending about the X-axis is combined

233    with twisting.  It can be concluded that the soil stiffness plays a vital role in the vibration responses of

234    the structure due to ground-borne vibrations.

235    **4.  Conclusions**

236    The rapid growth in railway infrastructure demand has meant an increase in the capacity of trains is

237    necessary. Ground borne vibration intensity has increased due to the increase in train speed, and other

238    factors related to vibration source, vibration path and receiver. The mast structure located alongside the

239    railway track is a support for overhead line equipment (OHLE) to supply the electric power to the train.

240    In practical work, the structures are designed with the assumption of having fixed support. In reality,

241    there is a small displacement created by the supporting soil. Hence, a three-dimensional mast structure

242    is created using a finite element package, STRAND7, with the consideration of soil-structure

243    interaction. The obtained results show that the resonance effect occurs and will amplify the effects of a

244    ground motion, causing a structure to suffer more oscillation. It is also noticed that the vibration

245    responses are dominant at the train location near the mast structure, whereas the response decreases

246    rapidly with the increasing distance. The largest displacement occurs when the train moves past the

247    mast structure at the track perpendicular to the structure. It is also observed that the first twisting mode

248    can occur when the train is run past the 45 degrees from cantilever mast. The soil stiffness beneath the

249    structure also plays a role in the reduction of resonance phenomenon. Nonetheless, there are some

250    limitations in this study. The ground borne vibrations are formulated by the prediction model with only

251    one frequency, whereas the ground vibration velocity has more than one dominant frequency in reality.

252    Therefore, there should be more than one resonance frequency. It is also recommended that there should

253    be further field measurement. However, the results obtained can be used as tolerances for the

254    consideration of further design standard before the effect of extreme events will be considered. The

255 outcome of this study will help provide a better understanding of the critical responses and behaviour

256 of mast structure under normal operation of high speed train. It is the first investigate to demonstrate

257 the effect of ground borne vibration generated by high speed train on the cantilever mast structure and

258 contact wire system.

259 **Acknowledgements**

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