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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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Abstract: At present, railway infrastructure experiences harsh environments and aggressive loading 12 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 is, for one or two tracks, normally supported by cantilever masts. A cantilever mast, which is made of 15 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. Nonetheless, mast structures, which are located nearest and alongside the railway track, have not been 18 fully studied in terms of their dynamic behaviour. This paper presents the effects of ground borne 19 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 wire in transverse direction. The results show that the effect of vibration velocity from train on the 26

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.

32 Keywords: Ground borne vibration, overhead line equipment, mast structure, vibration, soil-structure33 interaction

34 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).

42 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 43 lead to the failure of the electrical system (Shing and Wong, 2008; Robinson and Bryan, 2009; Taylor, 44 2013). This is because when the frequency of ground motion matches the natural frequency of a 45 structure, it will suffer the damage and large oscillations because of the occurrence of resonance effect 46 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 surrounding area (Connolly et al., 2016). The vibration level depends on many factors such as train 50 speed, ground condition, type of structure concerned etc. The effect of ground borne vibration on the 51 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 might not cause damage to the structure, this may cause annoyance to the people in the building 54 (Suhairy, 2000; Lopes et al., 2016). Cantilever mast structures have not been fully studied. In practice, 55 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, 2012), different soil support conditions were taken into account. It was noted that soil-structure 58 interaction affected the overall response of the structure. As for mast structure, it was noticeable that 59 60 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 61 behaviour was characterized by coincident eigenfrequencies, mode order change, while the 62 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 spectra are normally in the range of 0.5Hz to 80Hz (Jonsson, 2000) depending on wheel-rail 65 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.

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.

75 **2.** Methodology

76 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/m³. Poisson's ratio is 0.25.



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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).

89 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.

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.

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
$$F_s = \left(\frac{s}{s_0}\right)^A \tag{2}$$

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.

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

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

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. 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.





128

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.



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 137 138 direction, it can be seen that the vibration intensity increases when the train runs close to the mast 139 structure. It should be noted that when the train is located perpendicular to the mast, the vibration 140 velocity occurs only in transverse direction. The increase of angle leads to the higher vibration in this 141 direction. As for the longitudinal direction, the ground vibration increases until the angle of the train 142 reaches 45degrees and slightly decreases until the train is located perpendicular to the mast. This is 143 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 144 ground borne vibration velocity. Therefore, the maximum vibration velocity occurs at the angle of 145 45degrees. 146



136

148 149 **Figure 4** Ground borne vibration velocity at various distances from the track at a speed of 100km/h,

200km/h and 300km/h.

150 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 156 overhead wire, in both directions at various soil stiffness. It can be seen that, for higher stiffness from 157 about 100000kNm/rad to infinity, the displacements are very small compared with the lower stiffness. 158 As expected, when the mast is located on the very poor support condition corresponding to the stiffness 159 of 1000kNm/rad, the displacement is more than 5 times higher than that of the well support. In Figures 160 161 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.





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

181 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 182 results indicate that the RMS displacement trend has a rapid increase when the train runs to and angle 183 184 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 tolerances of contact stagger is considered as allowable movement in transverse direction (Railcorp, 188

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194

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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

197 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. 198 When the soil stiffness decreases, the dominant frequencies are reduced with a higher magnitude of 199 200 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 occurrence of large displacement. It is clearly seen that the dynamic behaviour of the mast structure, as 202 mentioned (Ngamkhanong et al., 2017), is relevant to the dominant frequencies, as shown in Figure 8. 203 It is interesting to note that there are two peaks of displacement observed when the mast has a poor 204 205 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



c)

209 210

211

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) directionc) 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 stiffness at the frequencies of 1.07Hz and 0.87Hz. It should be noted that the fundamental mode of 213 twisting for mast structure with rotational stiffness higher than 10000kNm/rad and 1000kNm/rad are 214 215 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 100000kNm/rad, when the ground vibrates at a frequency of around 1.07Hz, the rotations of the 217 cantilever observed are very small because of the well or rigid support conditions. The maximum 218 rotation can be observed when the train runs past the angle of 45 degrees and leads to the rotation of 219 220 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 221 condition. It is interesting to note that there is a more than tenfold higher rotation of the cantilever of 222 the mast because of the occurrence of the resonance effect. It should be noted that the resonance 223 224 vibration on the mast structure with the lower soil stiffness is higher than that with higher soil stiffness.

d)



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) 10000kNm/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.

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 is created using a finite element package, STRAND7, with the consideration of soil-structure 242 interaction. The obtained results show that the resonance effect occurs and will amplify the effects of a 243 ground motion, causing a structure to suffer more oscillation. It is also noticed that the vibration 244 245 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 246 mast structure at the track perpendicular to the structure. It is also observed that the first twisting mode 247 can occur when the train is run past the 45 degrees from cantilever mast. The soil stiffness beneath the 248 249 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 250 one frequency, whereas the ground vibration velocity has more than one dominant frequency in reality. 251 252 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 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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