

# 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**

3

4

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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.

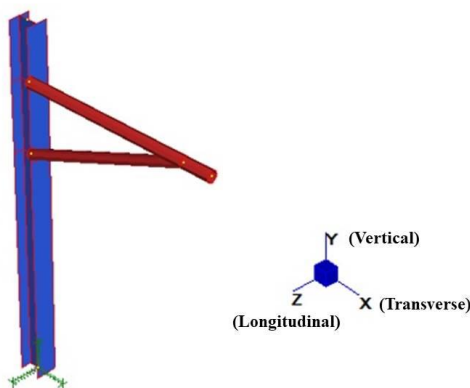
69 The present paper aims to study the effect of ground borne vibration generated by high speed trains on  
70 mast structures, with consideration of its underlying soil properties. Finite element model is employed  
71 to calculate the structural responses and the ground borne vibration is computed 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  $2 \times 10^5$  MPa with a density of  $7850 \text{ kg/m}^3$ . 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  $1000 \text{ kNm/rad}$  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 
$$V = V_T F_S F_D F_R F_B \quad (1)$$

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 
$$F_S = \left(\frac{S}{S_0}\right)^A \quad (2)$$

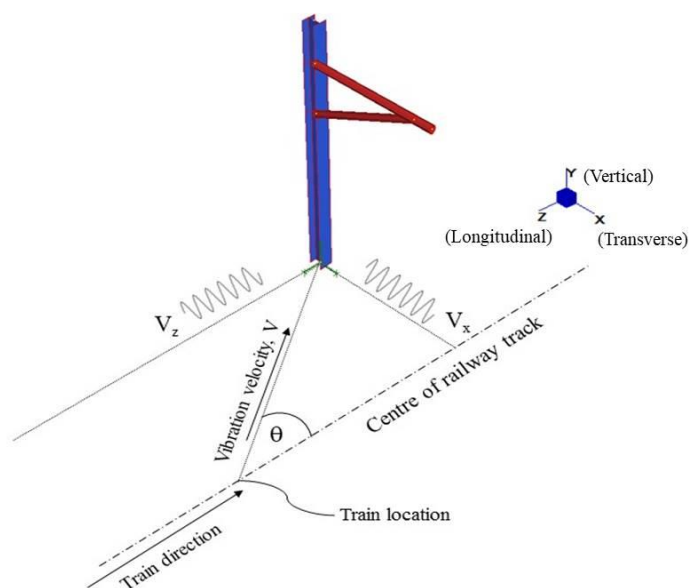
104 Distance factor,  $F_D$ , can be calculated as shown in Eq.3 where  $D$  is the distance from the centre of the  
105 track to the receiver,  $D_0$  is the reference distance from the centre of the tracks and  $B$  is the distance  
106 exponent.

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

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  $D_0 = 20\text{m}$ , from the centre of the  
112 tracks, when a train of the specified category passes at reference speed of  $S_0 = 70\text{ km/h}$ . 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.

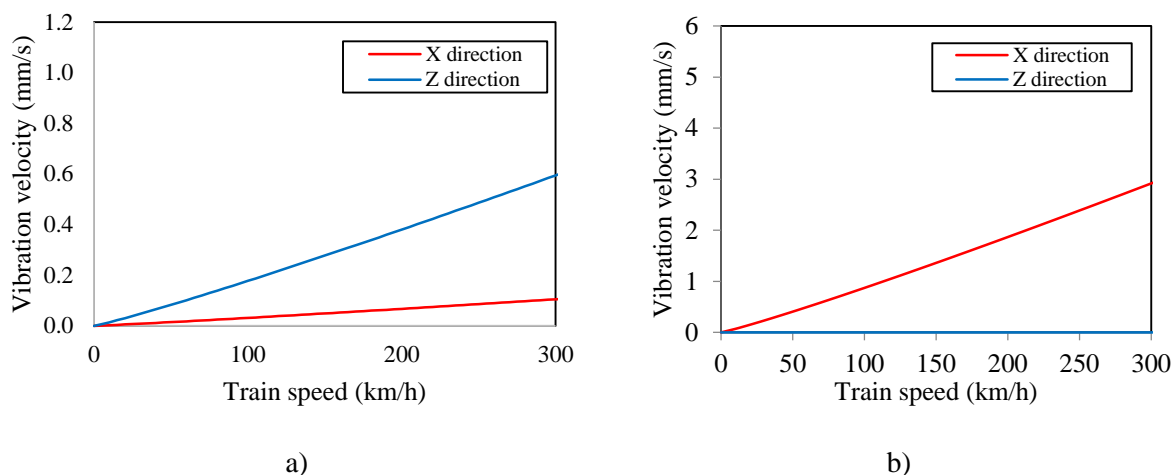
120 It is assumed that the mast structure is located at a distance of 3.5m perpendicular to the track. The train  
 121 speed varies from 100km/h to 300km/h. The ground vibration velocities created by train are inputted in  
 122 both directions as seen in Figure 2. When the train moves on the track, 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

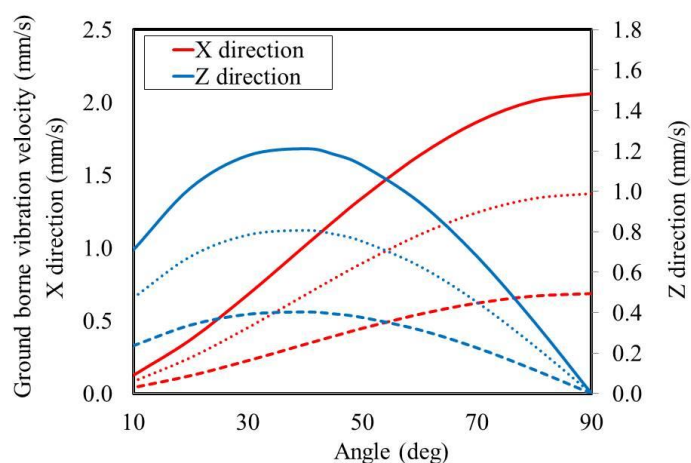
128 **Figure 2** Location of the cantilever mast structure and direction of train on railway track.

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.



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

137 The ground-borne vibration velocity calculations in both directions are shown in Figure 4. In transverse  
 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  
 144 stated in the previous section. In addition, the train speed increases and decreases with the same rate as  
 145 ground borne vibration velocity. Therefore, the maximum vibration velocity occurs at the angle of  
 146 45degrees.



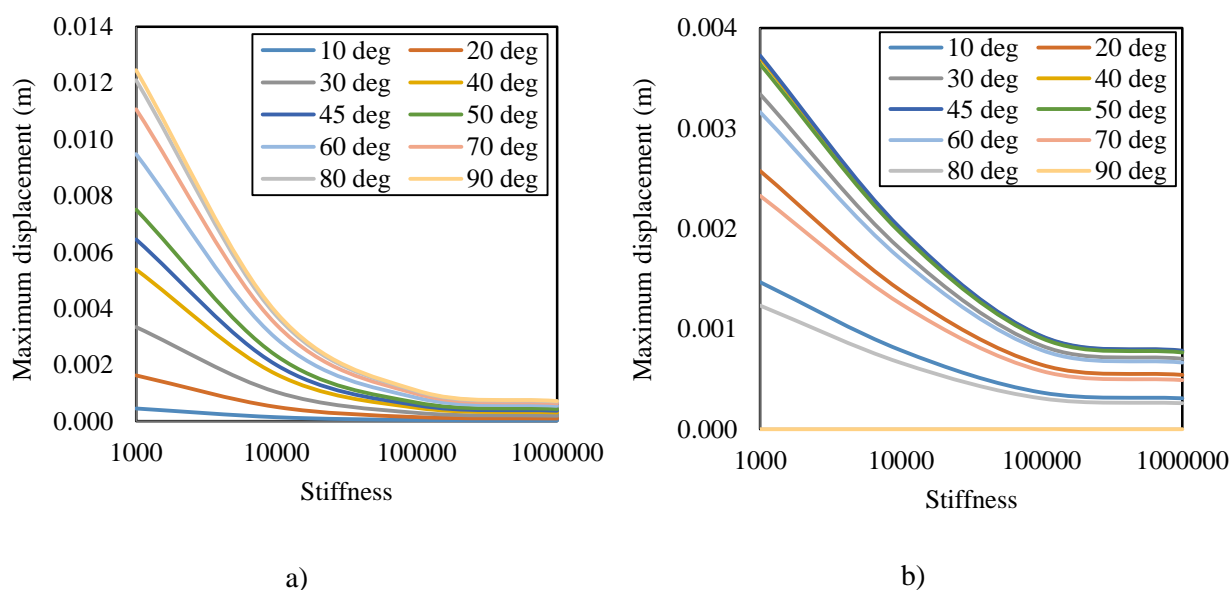


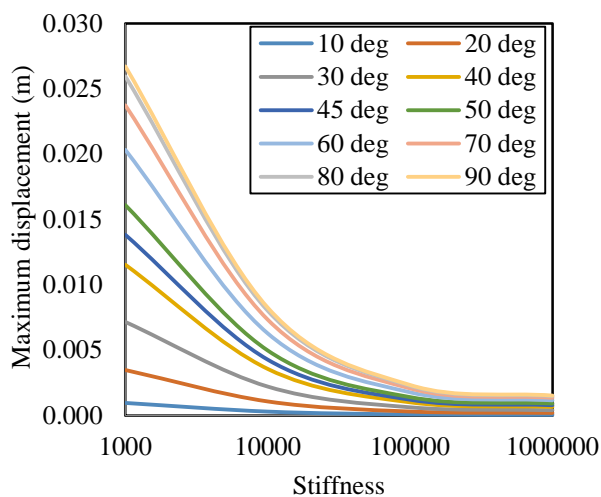
148 **Figure 4** Ground borne vibration velocity at various distances from the track at a speed of 100km/h,  
 149 200km/h and 300km/h.

### 150 3. Results and Discussion

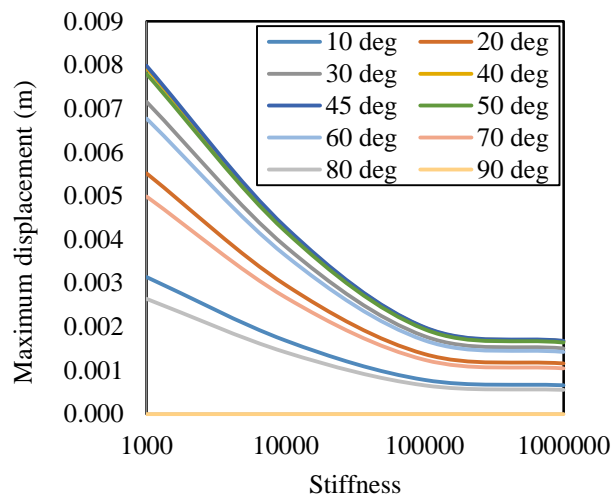
151 In this study, the frequency ranges between 1 and 100Hz are considered to cover the fundamental mode  
 152 shapes of the mast structure. Based on previous study (Ngamkhanong et al., 2017), the first, second and  
 153 third modes are twisting, bending about transverse, and bending about longitudinal, 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.

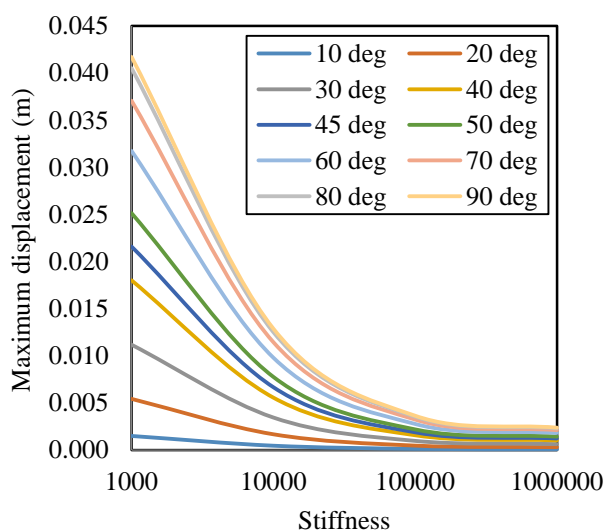




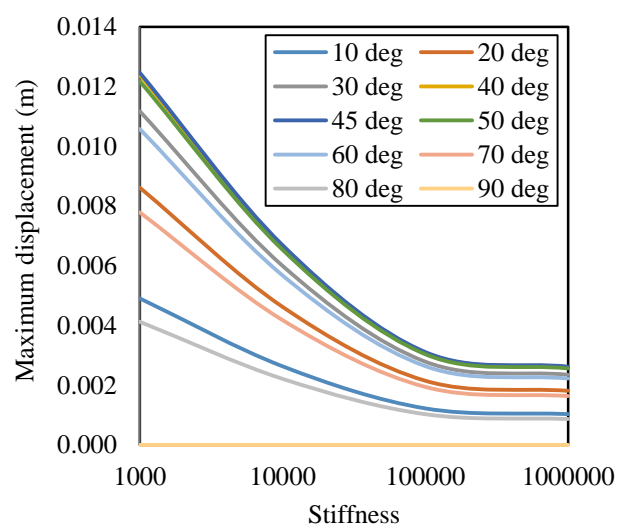
c)



d)



e)

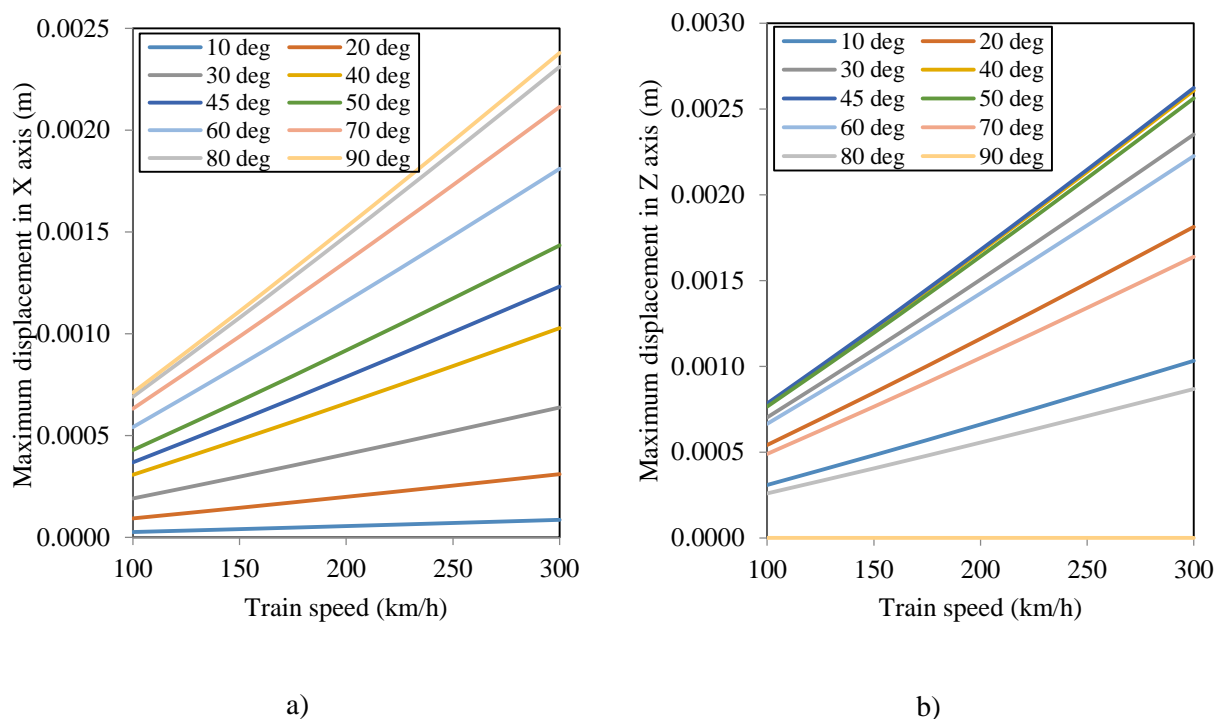


f)

165 **Figure 5** Maximum displacement at the position of overhead wire on cantilever mast at various angles  
 166 and soil stiffness a) 100km/h in X (transverse) direction b) 100km/h in Z (longitudinal) direction c)  
 167 200km/h in X (transverse) direction d) 200km/h in Z (longitudinal) direction e) 300km/h in X  
 168 (transverse) direction f) 300km/h in Z (longitudinal) direction.

169 At fully fixed support condition or rigid soil, it is clearly seen that the train speed plays a little role on  
 170 transverse direction when angles of the train to the mast are in low range (less than 30 degrees) but  
 171 plays a significant role at higher angles, as shown in Figure 6. For 70-90 degrees, it should be noted  
 172 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.

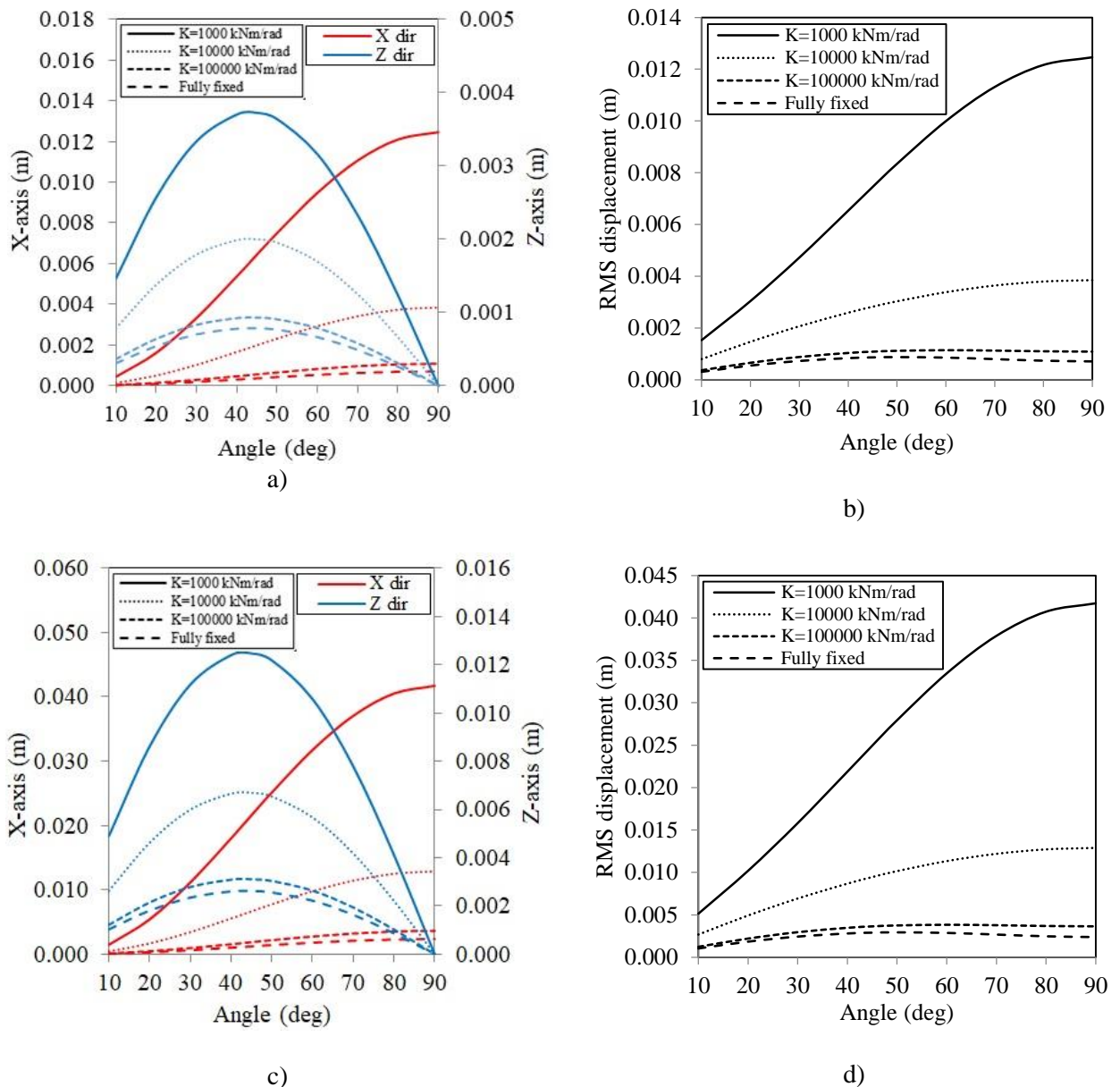


179 **Figure 6** Maximum displacement of mast at various train speeds and angles with fully fixed support  
 180 condition in a) X (transverse) direction b) Z (longitudinal) direction

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 an 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

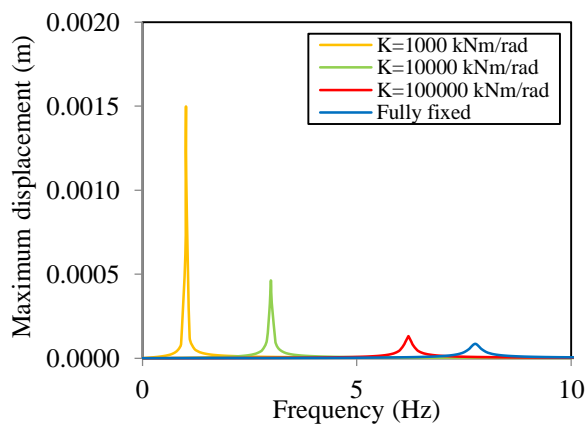
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100km/h in a) X (transverse) and Z (longitudinal) directions b) Root mean square

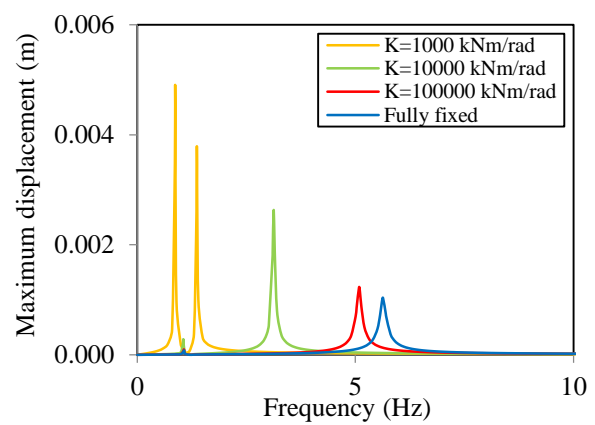
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300km/h in c) X (transverse) and Z (longitudinal) directions d) Root mean square

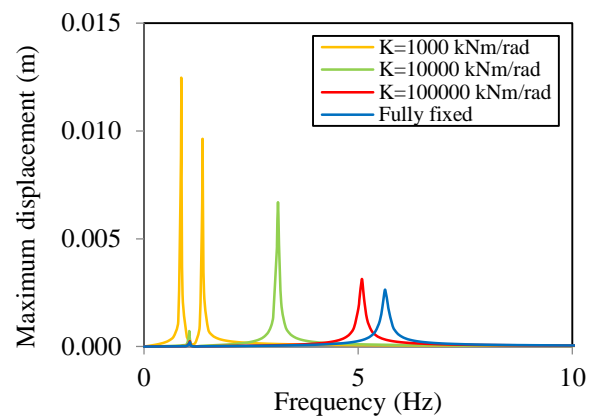
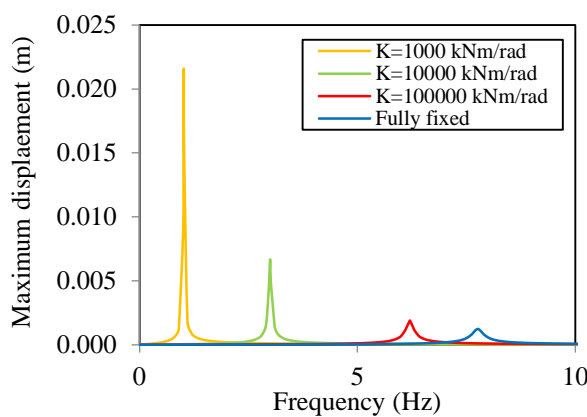
197 Figure 8 shows the frequency response of the maximum displacement in both directions. It can be seen  
 198 that the fundamental frequencies change due to the change of soil stiffness beneath the mast structure.  
 199 When the soil stiffness decreases, the dominant frequencies are reduced with a 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)

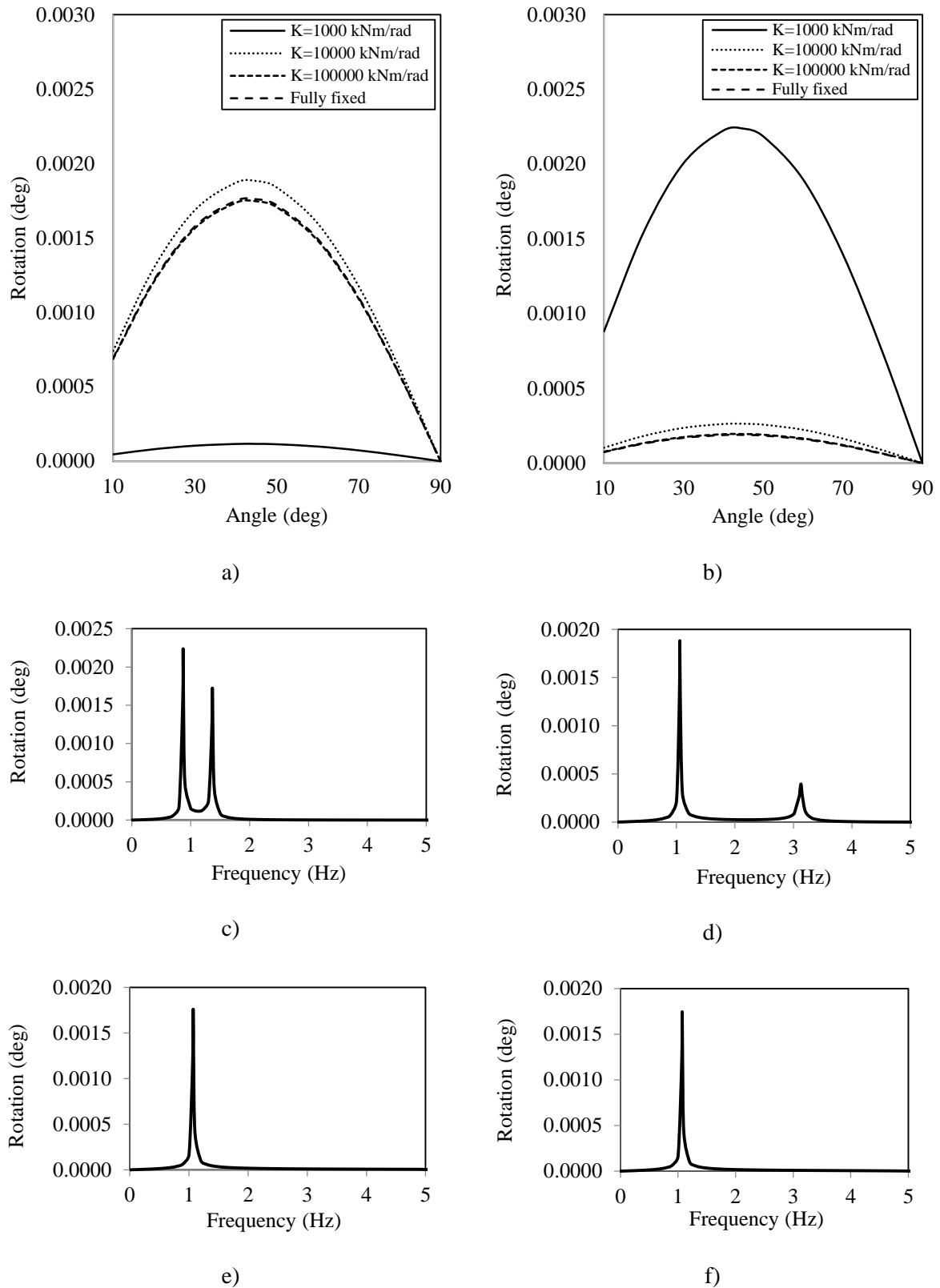


c)

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.



225 **Figure 9** Cantilever rotation at train speed of 300km/h around Y axis at the frequency of a) 1.07Hz b)  
 226 0.87Hz and frequency response of the rotation of cantilever mast with soil stiffness of c)  
 227 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.

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263 Infrastructure Systems Engineering Network”, which enables a global research network that tackles the  
264 grand challenge of railway infrastructure resilience and advanced sensing in extreme environments  
265 ([www.risen2rail.eu](http://www.risen2rail.eu)).

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