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DOI:
10.1007/978-3-030-34252-4_6

Document Version
Peer reviewed version

Citation for published version (Harvard):
Ngamkhanong, C, Kaewunruen, S, Calçada, R & Martin, R 2019, Failure of Overhead Line Equipment (OHLE) Structure under Hurricane. in *Innovative Solutions for Soil Structure Interaction: Proceedings of the 3rd GeoMEast International Congress and Exhibition, Egypt 2019 on Sustainable Civil Infrastructures – The Official International Congress of the Soil-Structure Interaction Group in Egypt (SSIGE).* Sustainable Civil Infrastructures , Springer, pp. 54-63, 3rd GeoMEast International Congress and Exhibition, Egypt 2019 on Sustainable Civil Infrastructures, Cairo, Egypt, 10/11/19. https://doi.org/10.1007/978-3-030-34252-4_6

Failure of Overhead Line Equipment (OHLE) Structure under Hurricane

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ABSTRACT: Presently, in modern railway systems, train or rolling stocks are powered by electricity through the overhead wire or the third rail on ground. Overhead line equipment (OHLE) is the component for the electric train which provides electric power to the train. OHLE is, for one or two tracks, normally supported by cantilever masts. OHLE is one of vulnerable components in railway system due to its slenderness. Note that, as previously recorded, the strong hurricane caused substantial damage over the large area and possibly knocked the train out of the track and cause electricity failures on OHLE. In fact, cantilever mast subjected to wind and hurricane actions may fail due to the incorrect design, material defects, improper support connections and its foundation etc. In this study, a mast structure with varying rotational soil stiffness is used to construct dynamic influential lines for soil-structure integrity prediction. Finite element model updating technique has been used to perform the dynamic responses of OHLE considering soil-structure interaction of OHLE. The scaled hurricanes at various magnitudes are applied to the OHLE. It is interesting that the support condition plays a significant role in the dynamic responses of OHLE under strong hurricanes. The obtained results demonstrate that the strong hurricane can cause a catastrophic damage to the OHLE which is linked to the failure of electric train. The insight will raise the awareness of engineers for better design of cantilever mast structure and its support condition.

INTRODUCTION

Overhead Line Equipment (OHLE), which consists of masts, gantries, wires found along electrified railways, is the component for the electric train to supply power to make electric trains move, It is important that electric train has become the efficient railway system that emits less carbon and is allowed to run quicker and more frequent for the sudden growth of passengers and journeys (RailCorp, 2011). OHLE is supported by the mast structures located alongside the railway line. However, due to the loss of contact between pantograph and contact wire, the electric system may be failed. There are some reasons that can possibly make a loss of contact wire such as wind, temperature, broken tree, snow storm, train derailment, track buckling etc (Shing and Wong, 2008; Robinson and Bryan, 2009; Taylor, 2013; Beagles et al., 2016).

Due to the effects of global climate change, all the natural disasters tend to have higher intensity and occur more frequent. It should be noted that strong wind and hurricane can knock the structure down as can be seen in many evidences occurred such as billboard, lattice tower, lighting pole etc. (Letchford, 2001; Tamura and Cao, 2009; Ramalingam, 2017; Li et al., 2018). As for railway track infrastructure, if the wind becomes strong enough to form a hurricane, the trees next to the train lines might fall and hit the overhead contact wires or knock down the mast structure (Network Rail, 2017), thereby leading to the failure of the electrical power system. For one or two railway tracks, OHLE is normally supported by single cantilever mast structure. It is interesting to note that the main reasons of damage and failure of mast structure are the poor of support structure, such as such as broken bolt, yielding weld, improper design and construction, and the dynamic sensitivity due to its slenderness by nature leading to the loss of contact wire.

The cantilever mast is a vibration-sensitive structure since crossing phenomena can be observed when the support stiffness is changed (Ngamkhanong et al., 2017). It was confirmed by previous studies that soil-structure interaction affected the overall response of the structure (Prum and Jiravacharadet, 2012; NEHRP, 2012).

FIG. 1. Single mast structure supporting OHLE

Due to the change of global climate, hurricane or strong wind may cause damage to the OHLE structure by losing the contact between pantograph and contact wire which can lead to operational failure of train electrification. The integrated numerical study of three-dimensional cantilever mast structure under the strong wind is presented to evaluate the condition of OHLE structures for maintenance planning. The condition of OHLE can be monitored using adaptation technique by finite element package STRAND7 (G+D Computing, 2001). Wind actions are calculated by the formulation based on the standard of wind actions on structures. The lateral displacement of the contact wire on the cantilever is measured to be able to properly inspect the contact wire condition. The soil-structure interaction is also taken into account. This study presents the maintenance index which can be used for maintenance planning and inspection of support condition of mast and OHLE structures. The outcome of this study will help civil and track engineers to effectively and efficiently inspect OHLE structures and its support using the structural response from wind actions.

METHODOLOGY

Modelling

Three-dimensional modelling of single mast structure is constructed using finite element package STRAND7 (G+D Computing, 2001).The linear static solver is used based on the assumprion that structure is in linear range and loading is static. The single cantilever mast structure made by steel is constructed, FIG 1. The 2-D schematic load to structure with support springs is shown in FIG 2. The typical H-section steel (Section area: $2.219 x 10^{-2} m^2$, I_{zz}: $5.08 x 10^{-4} m^4$, I_{xx}: $1.84 x 10^{-4} m^4$) is used and connected to the cantilever which made of round steel to support the overhead contact wire. The steel used has the young modulus of $2 x 10^5$MPa, density of 7850kg/m^3 and poisson's ratio of 0.25. The rotational and translational springs are applied at the support. The parametric study of the soil stiffness is conducted. It is assumed that translational stiffness of support is fully fixed in all directions, while the rotational stiffness is varied from 500 to 1000000kNm/rad (fully fixed support condition). It is noted that the rotational stiffness is affected by the soil-structure interaction condition and the quality of support connection (Kanvinde et al., 2012; Rodas et al, 2017; Krystosik, 2018). The support stiffness can be decrease due to the connection failure such as broken bolt, yielding weld, improper design and construction etc. and soil erosion and degradation. It is noticeable that the soil-structure interaction plays a significant role in the sensitivity of structural vibration. The quality of support connection and ground condition considerably influences the soil-structure stiffness (Ngamkhanong et al., 2017).

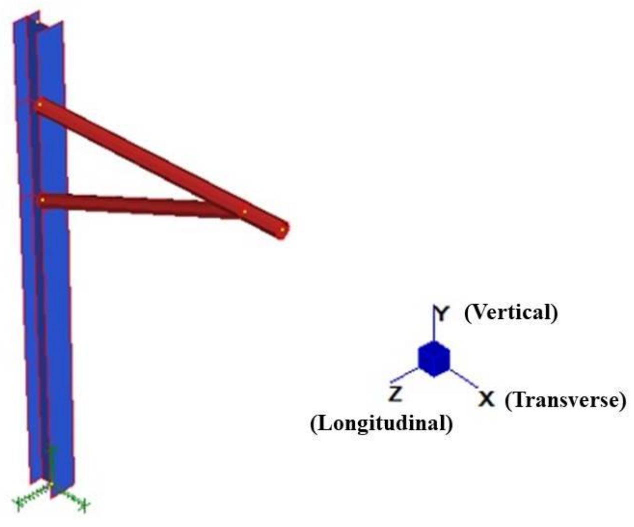
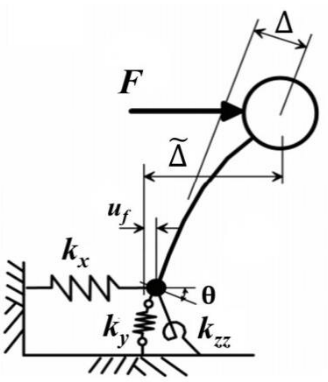


FIG. 2. 3-Dimensional model of OHLE

a)

b)



(c)

FIG. 3. Support of a) cantilever mast b) frame mast and c) Schematic load to structure with rotational flexibility at support

Wind action calculation

The wind action calculated from the wind velocity is presented by a static pressures or forces acting on the face of structure (BSI, 2005; BSI, 2006; BSI, 2012). The wind actions are characteristic values depending on the type and location of structure. The steps of wind force calculation are shown below.

The turbulence intensity and mean wind pressure at the reference height above ground, h, can be calculated using Eq. 1 and 2, in order to further compute the peak wind pressure.

$$I_V(h) = 1/[c_0 \ln\left(\frac{h}{z_0}\right)] \quad (1)$$

Where c_0 is the orography factor, z_0 is the roughness length.

Note that the recommended value is 1 for both c_0(when the average slope of the upwind terrain is small) and z_0(value for the area in which at least 15% of the surface is covered with buildings which average height exceeds 15m) as the worst case scenario.

$$q_h(h) = \frac{1}{2}\rho V_h^2(h) \quad (2)$$

Where ρ is the air density (kg/m^3). A conservative value for ρ is 1.25kg/m^3 given in BS EN1991-1-4 (BSI, 2005). $V_h(h)$ is the mean wind velocity (m/s) calculated by Eq. 3.

$$V_h(h) = V_{b,0} c_{dir} c_o k_r \ln(\frac{h}{z_0}) \quad (3)$$

Where $V_{b,0}$ is basic wind velocity (m/s), c_{dir} is wind directional factor (The recommended vale is 1), c_o is orography factor (taken as 1), k_r is the terrain factor ($k_r = 0.19\left(\frac{z_0}{z_{0,II}}\right)^{0.07}$)

The peak wind pressure at the reference height above the ground h is determined using Eq. 4.

$$q_p(h) = [1 + 7I_V(h)]q_h(h) \tag{4}$$

Where $I_V(h)$ is the turbulence intensity.

$q_h(h)$ is the mean wind pressure.

Based on BS EN 50341-1:2012 (BSI, 2012), wind action on the overhead line is basically calculated by the wind pressure acting multiplied by the projected area and structural factors. In this case, the wind force acting on mast structure can be determined by the Eq. 5 based on the assumption of the wind forces acting on poles.

$$Q_w = q_p(h)GCA \tag{5}$$

Where G is the structural factor, the recommended value is 1. C is the drag factor (1.8 is used for steel with sharp edge cross section. A is the projected area on a vertical plan perpendicular to the wind direction.

Hurricane wind speed

The scale was developed in 1971 by civil engineer Herbert Saffir and meteorologist Robert Simpson, who at the time was director of the U.S. National Hurricane Center. The U.S. National Weather Service, Central Pacific Hurricane Center and the Joint Typhoon Warning Center define sustained winds as average winds over a period of one minute, measured at the same 33 ft (10.1 m) height and that is the definition used for this scale (Federal Emergency Management Agency, 2004; Tropical Cyclone Weather Services Program, 2006). These velocities are then used to calculate the static force to apply to the cantilever mast. Hurricane's sustained wind speed can be classified into 5 categories based on potential property damage, as shown in Table 1.

Table 1. Hurricane wind scale and types of damage (Tropical Cyclone Weather Services Program, 2006)

Category	Wind speed	Types of Damage Due to Hurricane Winds
1	74-95 mph 64-82 kt 119-153 km/h	Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph 83-95 kt 154-177 km/h	Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	111-129 mph	Devastating damage will occur: Well-built framed homes may

	96-112 kt 178-208 km/h	incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4	130-156 mph 113-136 kt 209-251 km/h	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	157 mph or higher 137 kt or higher 252 km/h or higher	Catastrophic damage will occur: A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Note: National Hurricane Center classifies hurricanes of Category 3 and above as major hurricanes, and the Joint Typhoon Warning Center classifies typhoons of 150 mph or greater (strong Category 4 and Category 5) as super typhoons.

The linear static analysis is used for wind action. The loads obtained by the calculation are applied to the mast structure in perpendicular direction. The nodal displacement at the cantilever, which is the location of contact wire, are taken into consideration and will be compared with the maintenance index. The ratio between the overhead contact wire displacement and allowable displacement is indicated as maintenance index. It is assumed and noted that the allowable displacement used is the construction tolerances of contact stagger above the track to avoid wearing a groove in the pantograph according to RailCorp (2011). The construction tolerance of 50mm of contact wire is used as the allowable lateral displacement. Thus the maintenance index is the value between 0 and 1. The pantograph can possibly lost contact with the contact wire when the maintenance index reaches 1.

Results

The applied forces equivalent to the wind speed up to 300 km/h are applied to the mast structure. The displacement response of the mast structure in transverse direction subjected to the hurricane is presented in FIG. 4. The displacement response at the cantilever mast is then used to calculate the maintenance limit. The rotational stiffness considered is between 500 and 100000kNm/rad (fully fixed support).

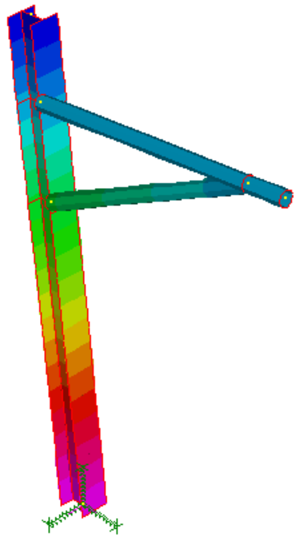
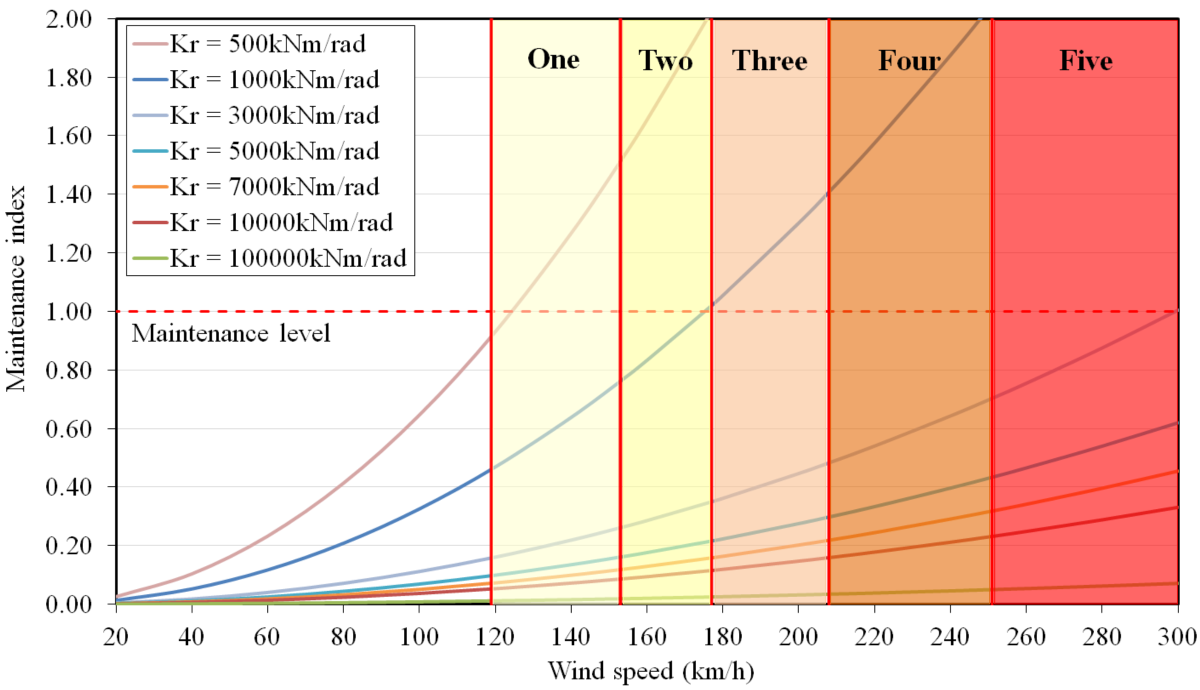
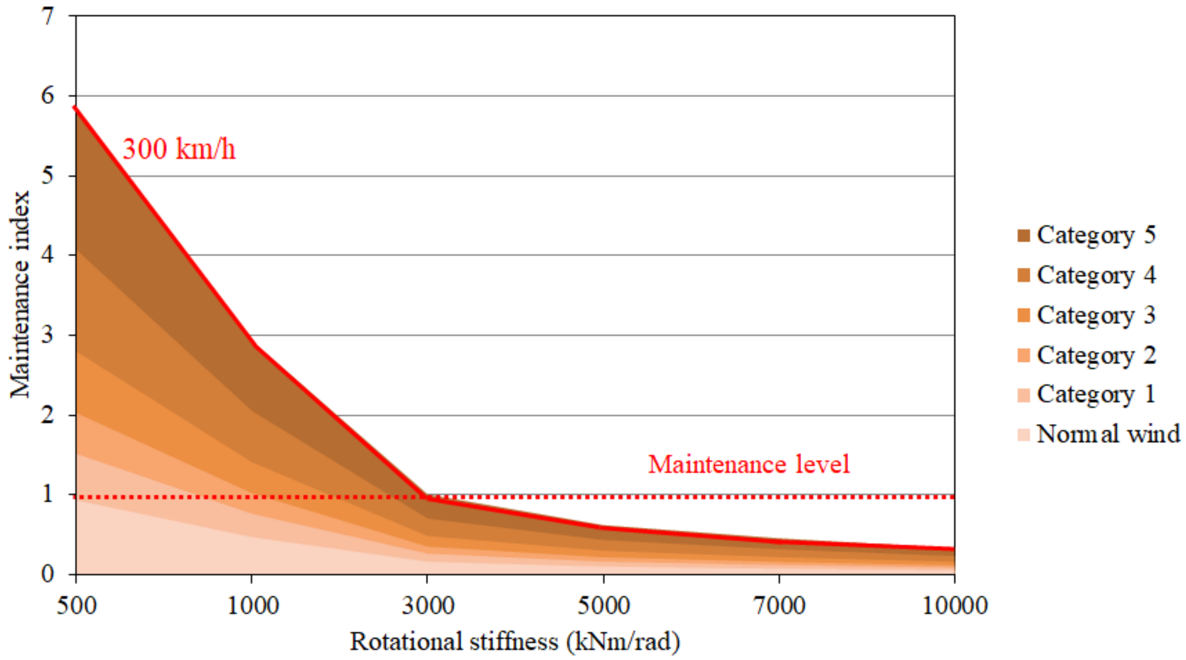


FIG. 4. Structural response of the mast structure subjected to hurricane.



(a)



(b)

FIG. 5. Maintenance index

The maintenance index of the OHLE at various stiffness conditions under different wind speed is presented in FIG. 5. It is clear that the strong wind or hurricane can significantly knock the electric system of the train. The results shown that the maintenance level can be reached when the rotational stiffness of the support is lower than 3000kNm/rad which is represented by the poor support interaction such as low number of bolts, size of foundation, soil condition etc. It is noted that, the hurricane category one can possibly make a failure of the OHLE when the mast has the support stiffness of 500kN/rad. However, the effect of strong wind can be mitigated by improving the support stiffness to be higher than 3000kNm/rad. It is interesting to note that the strongest wind that has occurred, cannot fail the OHLE since the structure has a fully fixed support. The maintenance is only about 0.1 in this case.

CONCLUSIONS

This study presents the structural responses of mast structure and OHLE under the hurricane and strong wind. The contact wire displacement on cantilever mast is measure based on the assumption that the structure can be failed when the displacement reaches the certain limit resulting in losing the contact between pantograph and contact wire. Moreover, the structure-soil interaction is considered as this can effectively affect the dynamic properties of the cantilever mast. The results obtained show that the failure of OHLE subjected to strong wind can be observed when the structure-soil interaction has its rotational stiffness of lower than 3000kNm/rad. Hurricane category A could possibly lead to failure of OHLE with its support rotational stiffness of 500kNm/rad. It is noted that the normal wind tend to have no effect on the failure of OHLE as the highest maintenance index under wind observed is around 90% of failure. However, this study does not consider the effect of relative displacement as, in reality, there is a gap at the contact area which can induce the relative displacement. This aspect will be further studied. Therefore, the connection at support should be carefully designed and constructed. The insight will raise the awareness of engineers for better design of cantilever mast structure and its support condition to encounter the natural disasters and future uncertainties.

ACKNOWLEDGMENTS
The authors are sincerely grateful to the European Commission for the financial sponsorship of the H2020-RISE Project No. 691135 “RISEN: Rail Infrastructure Systems Engineering Network”, which enables a global research network that tackles the grand challenge of railway infrastructure resilience and advanced sensing in extreme environments (www.risen2rail.eu) (Kaewunruen et al., 2016).

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