Siting of Electrical Substations for Flood Resilience: Identification of Hazards and Vulnerable Assets

Citation for published version (APA):
Li, W., Cunningham, L., Mander, S., Schultz, D., Panteli, M., & Gan, C. K. (2022). Siting of Electrical Substations for Flood Resilience: Identification of Hazards and Vulnerable Assets. In *Proceedings of the 2022 MACE PGR Conference* (pp. 1-4)

Published in:
Proceedings of the 2022 MACE PGR Conference

Siting of Electrical Substations for Flood Resilience: Identification of Hazards and Vulnerable Assets

Wenzhu Li[1], Lee S. Cunningham[1], Sarah Mander[1], David M. Schultz[2,3], Mathaios Panteli[4], Chin Kim Gan[5]

{[1]Dept. of Mechanical, Aerospace and Civil Engineering, [2]Dept. of Earth and Environmental Sciences, [3]Centre for Crisis Studies and Mitigation}, The University of Manchester, UK, [4]University of Cyprus, CY, [5]Universiti Teknikal Malaysia Melaka, MY

Abstract—**Extreme weather events disrupt power-system assets, causing widespread and prolonged power outages. Proper siting of power-system assets can help stakeholders improve their resilience (i.e., the ability to withstand hazards and recover quickly from impacts) at the planning stage. However, resilience is context-dependent because different regions face distinct hazards and these damage power system assets differently. As such, the asset siting schemes for stakeholders involve a complex process of i) identifying hazards and vulnerable assets, ii) determining the failure mechanisms of assets under hazards and iii) weighing up the economic and social effectiveness involved in resilience enhancement measures. This paper will focus on the first step of the process, which is to demonstrate how to identify the most severe hazards (e.g., floods) and affected assets (e.g., substations), using Peninsular Malaysia as the study area. The results of this study can provide research objectives for the subsequent two steps: determining the failure mechanisms of assets subject to hazards, and developing resilience enhancement measures in the third step.**

I. INTRODUCTION

Electricity is key to human activities; however extreme weather events often damage power system assets and have accounted for 49.6% of major power outages [1]. For example, the 2014 floods in Malaysia shut down more than 10,000 substations, causing US$4.8 million in damage and affecting 200,000 electricity customers [2]. Typhoon Faxai (2019) saw severe damage to transmission lines and towers in Japan, leaving nearly 1 million customers without power [3].

Proper siting of power assets can help stakeholders improve power-system resilience during the planning phase. Ideally, assets should be built where they are needed to provide electricity and away from areas of high disaster risk. However, development constrains the land available for siting, so assets are sometimes sited in areas at risk of disasters, and the resilience of new power assets needs to be assessed at the time of siting. Moreover, being aware of how climate will change in the future at a particular location is key to developing long-term resilience to weather-related disasters.

Asset resilience assessment depends on hazard–infrastructure interactions, for instance, the impact of wind speed/path on transmission lines are distinct from the effect of flood depth/velocity on substations. In this context, the overall approach to developing a siting strategy consists of three steps: 1) identifying hazards and vulnerable assets; 2) determining the failure mechanisms of assets under hazards and 3) weighing up the economic and social effectiveness involved in resilience enhancement measures. This paper focuses on the first step, which will then inform the derivation of the failure mechanisms of assets subject to hazards, as well as the development of resilience strategies (being investigated in the authors' other works).

Overall, this paper chooses Peninsular Malaysia as the study area (as Malaysia is one of the countries covered by the UKRI's Global Challenges Research Fund [4], and our stakeholder TNB power company locates its business in the western half of Malaysia, i.e., Peninsular Malaysia), and describes how information, such as local historical records, topography, climate, and trusted news reports, were used to identify the major hazards (Section II) and the severely affected power-system assets there (Section III). Furthermore, Section IV briefly introduces subsequent steps of this siting project and how the approach relates to the wider picture. Note that new assets are the focus of the present work, the vulnerability of existing assets in a changing climate needs to be understood to develop appropriate resilience for the entire power system.

II. DOMINANT HAZARD IDENTIFICATION: FLOODING

As introduced in Section I, different hazards affect the power system in distinct ways, so it is crucial to identify the dominant hazard before studying the resilience of vulnerable power assets.

To begin with, local historical records can help give a quick picture of significant disasters in a particular place. For example, in Malaysia, statistics on the average annual natural hazard occurrence from 1980–2020 show that flooding is the principal and the most frequent disaster (Figure 1) [5], which is also supported by other records e.g., approximately 48% of disaster losses can be attributed to flooding in the past two decades [6].

Further, the topography and climate are such that most floods in Malaysia feature a significant depth (e.g., 1.5 m [7]), and are attributed to heavy rainfall. Specifically, Malaysia lies between 1°N and 7°N and has a tropical rainforest climate, thus recording abundant annual rainfall, e.g., most areas of Peninsular Malaysia experience 2,000 mm or more rainfall year-round [8], compared to Earth's average of 1,000 mm [9]. Throughout one year, the heavy rainfall during the Northeast Monsoon season (October–March) is more associated with flooding in Peninsular Malaysia. Figure 2 illustrates the typical monthly rainfall (1991–2020) for this season, which is higher than in other periods [5]. Daily or short-duration rainfall over this season often exceeded the extreme rainfall threshold of 150 mm/day [8], resulting in floods as shown in the first column of TABLE I.

Some statistics suggest that the future flooding situation could be even more critical in Peninsular Malaysia. During 2020–2039, there is a predicted significant rise in the average monthly rainfall from October (Figure 3), followed by the Northeast Monsoon season [10]. Such changes could worsen the monsoonal floods by causing higher flood depths and flows for the same timescale, this is exacerbated by the regional topography with plains in coastal areas and forested mountains in interior Peninsular Malaysia. Having understood that the dominant hazard in the study area is rainfall-induced flooding and that it is seasonal, the next section looks at what and how power assets will be affected, where flood depth and velocity will be the input data for failure analysis.

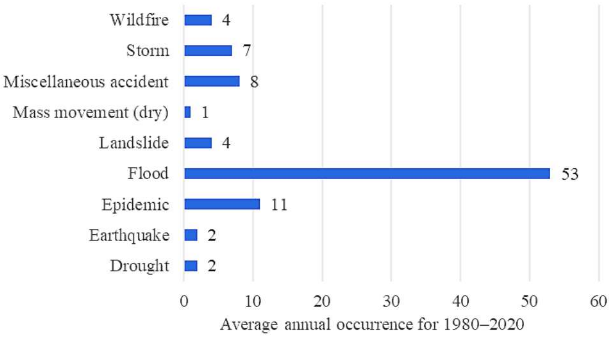

Figure 1. Average annual natural hazard occurrence in Malaysia for 1980–2020 (redrawn based on [5])

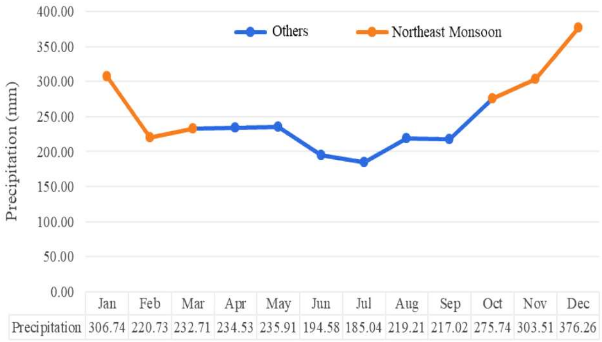

Figure 2. Average monthly rainfall in Peninsular Malaysia from 1991–2020 (plotted based on [5])

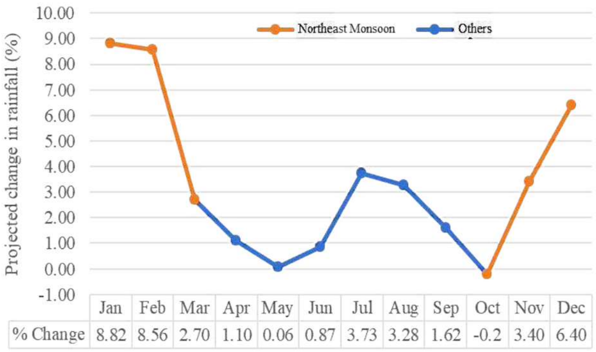

Figure 3. Projected changes in rainfall in Peninsular Malaysia during 2020-2039 (plotted based on [10])

III. FLOOD-PRONE POWER SYSTEM ASSETS: SUBSTATIONS

The impact of flooding on specific power system assets is not always clear as few details are documented beyond the flooding itself. Given the limitations, this study uses a media search to understand the impact of flooding on power assets. All the selected news sources are the most popular websites in Malaysia [11], including but not restricted to: Bernama, Malaysiakini, The Star, New Strait Times, Malay Mail, Berita Harian, Utusan Malaysia, 光华 Kwongwah, 星洲 Sinchew, 东方 Oriental Daily. These publications are available in either English, Malay or Chinese. Hence, when searching for flood-related news on these websites, the language differences in keyword searches need to be noted, e.g., flood is 'banjir' and electricity is 'elektrik' in Malay; while the flood is '洪水 hóng shuǐ' and electricity is '电 diàn' in Chinese.

The media search identifies that substations are the most frequently flooded power assets in Peninsular Malaysia. TABLE I reviews the damage caused to substations in some states by major floods in Peninsular Malaysia.

TABLE I. OVERVIEW OF AFFECTED POWER ASSETS & CUSTOMERS

Date and Region	Affected Power Assets	Affected Customers
Dec. 2013, Terengganu, Pahang, Johor [12]	1,072 and 141 substations were closed in Pahang, Terengganu, respectively	62,907 and 5,272 affected customers in Pahang and Terengganu
Dec. 2014, Kelantan, Pahang, Terengganu [13]	1,606 substations were suspended to avoid short-circuit	70,284 residents were left in darkness; >1,000 TNB employers worked in relief centres
Dec. 2014, Kelantan, Pahang, Terengganu, Perak [14]	>616 substations were shut down	152,660, 5,209 and 2,825 customers lost energy in Kelantan, Terengganu and Perak, respectively; 1,500 TNB personnel worked for energy restoration
Jan. 2015, Kelantan [15]	1,036 substations were shut down; RM10 million (USD 2.4 million) was lost on power infrastructure	30,309 customers; 30 gen-sets were installed in relief centres
Nov. 2017, Penang [16]	16 of 4,852 substations could still not be operational due to safety reasons	160 technical personnel worked for restoring the electricity supply; 33 gen-sets had been installed in relief centres and residential areas
Jan. 2021, Terengganu [17]	14 substations were shut down	849 customers
Jan. 2021, Pahang, Johor [18]	91 substations were shut down	2,300 customers in Pahang and 3,900 customers in Johor

As seen in TABLE I, major floods were recorded during the Northeast Monsoon (November-March), again indicating that most floods in Peninsular Malaysia are attributed to this season. Moreover, TABLE I shows that flooded substations will affect a large number of electricity consumers, interrupting electricity distribution to other critical infrastructures, such as factories and hospitals. However, the news reports only tell us the result i.e., shut down of substations, rather than which types of substations are vulnerable to flooding, or how substations fail during a flood. Thus, the failure mechanisms of substations need to be further explored.

Substations in Peninsular Malaysia are divided into four types according to voltage levels: 132/275 kV transmission main intake (PMU), 33/11 kV main distribution (PPU), 33/22/11 kV main switching station (SSU), 11 kV/415 or 240 V distribution substation (PE) [19]. Research indicated that, in Kelantan Peninsular Malaysia, all PMUs have high inundation failure probabilities, versus PPUs and SSUs (89%) and PEs (84%) [19]. As a result, PMUs are more vulnerable to inundation, while associated interruption can cause the greatest problems for power supply and security (e.g., PMU Tanah Merah plays a major role in the National Grid as it connects the north and east coasts of Peninsular Malaysia [20]).

In addition to classifying substations by voltage level and focusing on inundation failures (where the electrical gear comes into direct contact with water irrespective of depth or velocity), substations have a chance of structural failure when subject to fast floodwater flows, which can also be worsened by the topography mentioned in Section II and interactions with urban development.

Therefore, to study the structural failure mode, we further categorise substations into two configurations, chamber-housed and pole-mounted (Figure 4), based on the Substation Design Manual published by our stakeholder TNB [21]. Specifically, masonry walls in chamber-housed substations, where there is a reasonable level of water-tightness, may be structurally damaged by even slow-moving or still water if deep enough, due to hydrostatic pressure. Whereas, pole-mounted substations are also at risk of structural failure due to overturning in flood flows, even though the electrical equipment in this type of substation is elevated on poles and less vulnerable to failure by direct inundation of water [21].

Based on the above identification of inundation and structural failure modes, flood depth and flood velocity will be considered as key inputs to both the analysis of asset failure mechanisms (step 2) and resilience assessment (step 3) mentioned in Section I. Other work by the authors focuses on these issues and a high-level presentation is given in the next section.

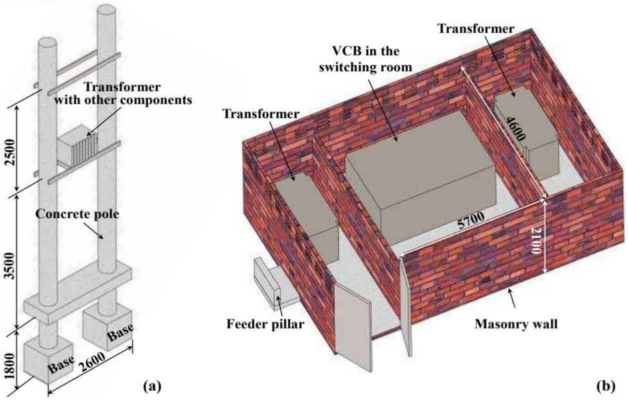

Figure 4. Common substation configurations in Malaysia: (a) typical pole-mounted substation; (b) typical chamber-housed substation (unit mm, redrawn using SOLIDWORKS, based on [21])

IV. SITING APPROACH FOR 'FLOOD-SUBSTATION' RESILIENCE

As stated in Section I, this study provides the first step in substation siting for flood resilience and gives the research objectives for subsequent steps 2 and 3, including deriving failure mechanisms and weighing the economic and social costs of resilience enhancement measures. Below presents the key methods used in the subsequent two steps of the siting project.

- Step 2: For future events, flood characteristics, such as depth and velocity, are obtained not by relying on incomplete historical records, but through hydrological modelling, using geo-referenced data (e.g., basins, digital elevation models, rainfall information for the study area). The inundation failure and structural failure criteria of the substation under different flood scenarios can also be determined by considering its flood protection level and structural capacity.
- Step 3: Based on the two failure modes of substations, i.e., inundation of the electrical equipment and structural failure of the substation housing, corresponding measures can be developed to enhance the resilience of the power system (e.g., installation of flood walls of a certain height, additional drainage facilities). This can help develop optimal siting solutions, which combine with the needs of the stakeholders and considers the economic and social benefits (e.g., power rescue deployment, economic losses from power outages).

Furthermore, the siting approach to 'flood-substation' resilience can be applied to locations worldwide. The New York Times commented that from 2000 to 2019, floods have disrupted at least 1.65 billion people, which is the highest number of all disaster categories. The examples listed in TABLE II constitute extreme flood events occurring during 2021 and underline the global problem faced by power system assets.

TABLE II. EXAMPLE EXTREME FLOODS WORLDWIDE IN 2021

Time	**Location**	**Flood condition (area, rainfall amount and duration)**
Dec. 2021 [22]	Malaysia	Eight states in Peninsular Malaysia; 24-hour rainfall up to 363 mm; the worst since the 2014 floods
Oct. 2021 [23]	Italy	Northwest region; 750 mm in 12 hours, a new European high for rainfall intensity and volume
Sept. 2021 [24]	United States	Central Park, New York; 24-hour rainfall of 180 mm; 1-hour rainfall of 80 mm
Jul. 2021 [25]	China	Henan Province; 201.9 mm of rainfall in 1 hour; maximum flood level of 79.4 m
Jul. 2021 [26]	Germany	Almost the whole country; maximum daily rainfall of 88.4 mm

Existing research shows that there is an upward trend in the number of extreme events (EM-DAT disaster database [27]). By 2040, 41% of the world's population will be at risk of flooding, with South/ Southeast Asia being the worst affected region, having over 2 billion people at flood risk [28]. The population in many of these areas are also facing urbanisation and a wider demand for electricity supply, which requires a resilience assessment of substation siting. In this paper, the three-step siting approach considers the spatial and temporal nature of flooding and will allow simulations of potentially more severe or more frequent flooding in the future.

V. CONCLUSIONS

Proper siting of power-system assets can help stakeholders to enhance power-system resilience at the investment planning stage. This paper discusses the first step in siting using Peninsular Malaysia as the study area, i.e., using local historical records (including climate and topography), popular news reports, and construction design manuals to identify the principal hazards there and the most severely affected power-system assets. The conclusions and implications are summarised below.

- Rainfall-induced flooding during the Northeast Monsoon is identified as the main hazard in Malaysia. Depth and velocity are two parameters that characterize flooding. For the next stage of this work, these parameters will be obtained via hydrological modelling and will be the input data for asset failure analysis.
- The most flood-prone power system assets are identified as substations. Substations are classified according to their voltage level and configuration; they may face inundation and structural failures. Both failure modes are being investigated in the present authors' other works, which will aim to inform stakeholders when, where and which substations will fail during resilience assessment.
- After completing the above two steps of analysis, the economic and social effectiveness involved in resilience enhancement measures can be further assessed to help stakeholders develop a comparatively optimal asset siting plan.
- This siting approach for 'Flood-Substation' resilience will relate to the wider picture, as there are many countries around the world that are also facing the effects of flooding, and these impacts are likely to become more severe in the future.

REFERENCES

[1] Qu, Y., Zhang, W., Ye, B., et al, 2021. Power outage mediates the associations between major storms and hospital admission of chronic obstructive pulmonary disease. *BMC public health*, *21*(1), pp.1-9. DOI: 10.1186/s12889-021-12006-x.

[2] New Straits Times. 2015. *TNB recorded RM20m losses of power infrastructure due to flood*. [online] Available at: https://www.nst.com.my/news/2015/09/tnb-recorded-rm20m-losses-due-flood.

[3] The Statesman. 2019. *Typhoon Faxai leaves a million without power in Japan - The Statesman*. [online] Available at: https://www.thestatesman.com/world/typhoon-faxai-leaves-a-million-without-power-in-japan-1502797899.html.

[4] UKRI. *Global Challenges Research Fund*. [online] Available at: https://www.ukri.org/what-we-offer/international-funding/global-challenges-research-fund/.

[5] World Bank. 2021. *Climate in Malaysia*. [online] Available at: https://climateknowledgeportal.worldbank.org/country/malaysia/climate-data-historical.

[6] Khan, M.M.A., Shaari, N.A.B., et al, 2014. Flood impact assessment in Kota Bharu, Malaysia: a statistical analysis. *World Applied Sciences Journal*, *32*(4), pp.626-634. DOI: 10.5829/idosi.wasj.2014.32.04.4.

[7] Jbarisk. 2021. *Super Typhoon Rai and South East Asia Floods*. [online] Available at: https://www.jbarisk.com/flood-services/event-response/super-typhoon-rai-and-south-east-asia-floods-a-retrospective/.

[8] Malaysian Meteorological Department. 2021. [online] Available at: https://www.met.gov.my/.

[9] Hypertextbook. 2022. *Volume of Earth's Annual Precipitation - The Physics Factbook*. [online] Available at: https://hypertextbook.com/facts/2008/VernonWu.shtml.

[10] World Bank. 2022. *Projections in Malaysia*. [online] Available at: https://climateknowledgeportal.worldbank.org/country/malaysia/climate-data-projections.

[11] AllYouCanRead. 2022. *Top 30 Malaysian Newspapers & News Sites*. [online] Available at: https://www.allyoucanread.com/malaysian-newspapers/.

[12] The Edge Markets. 2013. *1,072 electrical substations flooded in Pahang, power supply stopped - TNB*. [online] Available at: https://www.theedgemarkets.com/article/1072-electrical-substations-flooded-pahang-power-supply-stopped-tnb.

[13] New Straits Times. 2014. *Flood: TNB suspends 1606 substations in Pahang, Kelantan and Terengganu*. [online] Available at: https://www.nst.com.my/news/2015/09/flood-tnb-suspends-1606-substations-pahang-kelantan-and-terengganu.

[14] Malaymail. 2014. *616 TNB substations back in operation in flood affected areas*. [online] Available at: https://www.malaymail.com/news/malaysia/2014/12/28/616-tnb-substations-back-in-operation-in-flood-affected-areas/809809.

[15] Malaysiakini. 2015. *US offers disaster relief help to flood-hit areas*. [online] Available at: https://www.malaysiakini.com/news/285046.

[16] New Straits Times. 2017. *TNB sets up 30 mobile power generators in Penang's flood-hit areas*. [online] Available at: https://www.nst.com.my/news/nation/2017/11/299645/tnb-sets-30-mobile-power-generators-penangs-flood-hit-areas.

[17] The Malaysian Reserve. 2021. *TNB temporarily shuts down 14 substations due to floods*. [online] Available at: https://themalaysianreserve.com/2021/01/08/tnb-temporarily-shuts-down-14-substations-due-to-floods/.

[18] New Straits Times. 2021. *Floods prompt TNB to shut down 91 substations in Pahang and Johor*. [online] Available at: https://www.nst.com.my/news/nation/2021/01/654199/floods-prompt-tnb-shut-down-91-substations-pahang-and-johor.

[19] Rostam, N.E., Sidek, L.M., Basri, et al, 2016. Identification of Vulnerable Regions for TNB's Electric Substations during Flood in Peninsular Malaysia. *ISFRAM 2015*, p.67. DOI: 10.1007/978-981-10-0500-8_6.

[20] TNB. 2021. *Annual Report*. [online] Available at: https://www.tnb.com.my/suppliers-investors-media-relations.

[21] Scribd. 2022. *TNB Substation Design Manual*. [online] Available at: https://www.scribd.com/document/469973650.

[22] ADAM, 2022. *Record rainfall in Selangor passes 380mm mark, state government moves victims to relief centres*. [online] Malay Mail. Available at: https://www.malaymail.com/news/malaysia/2021/12/18/record-rainfall-in-selangor-passes-380mm-mark-state-government-moves-victim.

[23] Sky News. 2022. *Italy: 29 inches of rain in 12 hours sets new European record as extreme weather lashes country*. [online] Available at: https://news.sky.com/story/italy-29-inches-of-rain-in-12-hours-sets-new-european-record-as-extreme-weather-lashes-country-12428005.

[24] Nytimes. 2022. *Central Park sets a rainfall record*. [online] Available at: https://www.nytimes.com/2021/08/22/us/central-park-rainfall-record.html.

[25] Petley, D., 2022. *The extraordinary, almost unbelievable, rainfall in Henan Province yesterday*. [online] The Landslide Blog. Available at: https://blogs.agu.org/landslideblog/2021/07/21/henan-1/.

[26] laitimes. 2022. *Last year, the daily high temperature of 62 weather stations in China broke the extreme value*. [online] Available at: https://www.laitimes.com/en/article/20cd8_292gt.html.

[27] EM-DAT. 2022. *The international disasters database*. [online] Available at: https://www.emdat.be/.

[28] Serkez, Y., 2021. *Every Country Has Its Own Climate Risks. What's Yours*. [online] Available at: https://www.nytimes.com/interactive/2021/01/28/opinion/climate-change-risks-by-country.html.