Study and Evaluation of a Solar Floating Traction under Severe Wind Conditions

Pongwit Siribodhi*, Phacharaporn Bunyawanichakul

Design Clinic Research Unit, Department of Aerospace Engineering, Faculty of Engineering, Kasetsart University, 50 Ngam Wong Wan Rd., Ladyaow, Chatuchak, Bangkok, 10900, Thailand.

*Corresponding author e-mail: fengpws@ku.ac.th

Abstract. Solar cells have been among the first such clean energy groups that have been used, talked about, and adopted extensively in many areas. One drawback of using solar cells for energy supply not only in households but also in large cities is the space needed as well as usually requiring a flat area. For these reasons, the construction of solar farms over water is a popular concept and continues to be of interest in Thailand and the rest of the world. This research provided a case study of implementing large-scale solar cells in Southeast Asia where unexpected typhoons are common during the monsoon season. This can be addressed by binding the solar panels together to make a large platform that can remain intact in the water under various conditions. Engineers need to be confident that such binding will be safe enough to ensure the solar floating platform has no movement which may cause unexpected damage. This study developed and evaluated solar panel traction with an arrangement of 9 x 28 and 28 x 9 panels under severe wind conditions of 120 kilometers per hour (33.33 meters per second) which is equivalent to typhoons in the region. The evaluation used empirical and numerical models, and wind-tunnel testing. The resultant equation was: D (N, M) = 2075.8 N^{0.6532} M^{0.9052} and D = K_v (V) 2075.8 N^{0.6532} M^{0.9052} where N and M are the numbers of platforms in columns and rows, respectively, K_v (V) = (0.019564618+0.007704667V)/(1-0.0004656279V), and V is the wind speed (km/h). The investigation found that the predicted traction results using the derived equations was in good agreement with wind-tunnel testing for a proposed platform.

Keywords: Floating solar farm, Mooring system, Solar cell, Floating platform, Solar floating aerodynamics.

1. Introduction
There has been a steady increase in human energy consumption around the world. Previous generations had lower energy requirements than humans at present. It is clear that almost everyone has personal gadgets and smart appliances even with a modest lifestyle, which is leading to higher and higher everyday energy consumption. In 2015, a review reported that humans generally consume as much as 110 times as much energy per person as our early ancestors [1]. Nowadays, the main source of energy come from fossil fuels (coal, natural gas, oil). However, fossil fuels directly impact on the environment and they are nonrenewable resources. Therefore, a major step forward for humans, as the
world’s biggest polluter, is to in-vest in renewable energy sources. Clean energy is considered to be an alternative to traditional power sources such as coal, natural gas, and oil around the world.

There are many sources of renewable energy including solar energy, wind energy, hydropower, and bioenergy. Among these, solar and wind energy are exceedingly cheap to operate and their sources of energy are free. According to the World Energy Council [2], “the total energy from solar radiation falling on the earth was more than 7,500 times the World’s total annual primary energy consumption of 450 EJ” [3]. For this reason why people are looking for new developments to convert sunlight directly into electricity.

The installation of solar panels is more complex and difficult on a water surface requiring a different system than on land. A distinct difference is the aerodynamic loading and various unpredictable damage patterns. In addition, solar panel installation is generally used to produce large-scale capacity and requires an appropriate large, open space for ensuring energy production. A study concluded that a water surface installed with solar cells was 11% more efficient in electricity production than onshore solar cells [4]. The challenge in constructing solar panels on the water surface is related to the design, structural strength, and binding of the platform. In Southeast Asia every year, there are typhoons during the monsoon season. An average typhoon wind speed is approximately 120 kilometers per hour (33.33 meters per second) [5]. This means that a solar cell platform will be subject to aerodynamic loads from such wind speeds which can result in a traction force on the platform. Such a traction force, if high enough, may cause the platform to move or fall out of the alignment and lead to damage to the solar cells from collisions.

2. Scope of work
Since solar panels only generate electricity when the sun shines, to produce enough energy it is necessary to have a large area of solar panels apart from considering the efficiency of the solar cells in the panels. The more solar cells working, the more power they create. However, most manufacturers fabricate solar panels at a marketable size. It is essential to arrange a group of solar panels on a huge surface for the purpose of efficiency. In this study, 1,512 sets of solar cells were installed on a platform floating on a water surface. Each set was composed of 12 solar panels disregarding the under-water part as calculated using the static equilibrium equation [1,6-7] as shown in Fig.1. Different patterns in terms of the numbers of platforms in columns and rows, represented by N and M, respectively, were established to fit with the reservoir surface. An example of 15 sets where N x M equals 5 x 3 is illustrated in Fig.2.

![Fig. 1: Solar floating platform set](image1)

![Fig. 2: Arrangement of N x M representing 5 x 3](image2)
In this paper, the solar cell platform was actually constructed with several groups of 252 sets established in two main patterns of 9 x 28 and 28 x 9. The traction that occurred on the platform under the aerodynamic load at a wind speed of 120 kilometers per hour was calculated and evaluated. The investigation was performed on a 1:20 scaled model using wind tunnel testing in order to validate the calculation results. Finally, a closed form traction force equation with independent variables consisting of the number of platforms in a row, the number of platforms in a column and the wind speed was established. This equation was used to develop traction force criteria for estimating the anchor strength of the platform arranged in an operating pattern of 9 x 28 and 28 x 9.

3. Methodology
This study used three tools to calculate and evaluate the traction force on the platform: a closed form equation, computational fluid dynamics, and a wind tunnel test. There are recognized limitations in assessing traction force using each technique. Therefore, this study took advantage of the best components of each tool and these were used to validate each other. The results of the study can be summarized as follows:

3.1. Closed form equations [8]
According to the American Society of Civil Engineering Standard issued on ASCE7-10 Minimum Design Loads for Buildings and Other Structures, an open building with gable roof is subject to wind load as defined in Fig.3. The wind direction come from the left with no angle to the horizontal level. Two net pressure coefficients, $C_{NW}$ and $C_{NL}$, contributed from the top and bottom surfaces, shall be considered when the wind speed comes from the side of the buildings. The building has a horizontal dimension of roof, $L$, measured in the along wind direction, mean roof height, $h$, angle of plane of roof from horizontal, $\theta$ and wind direction, $\gamma (=0^\circ)$. For the case of an open building, the velocity pressure, $q_h$, evaluated at the mean roof height $h$ was calculated in SI unit using the following equation:

$$q_h = 0.613K_hK_{ht}K_dV^2$$  \hspace{1cm} (1)

where

$K_h =$ velocity pressure coefficient = 1.03 (exposure d-flat, unobstructed areas and water surfaces at height 0-4.6 m)

$K_{ht} =$ geographic factors = 1

$K_d =$ wind directionality factor = 0.85 (main wind force resisting system; MWFRS)

$V =$ wind speed = 33.33 m/s

For open buildings, the design pressure, $p$, was determined from the following equation:

$$p = q_hGC_N$$  \hspace{1cm} (2)

![Fig. 3: Wind loads on open buildings](image-url)
where
$q_h = \text{velocity pressure evaluated at mean roof height } h, \text{ determined from Eq. (1)}$

$G = \text{gust-effect factor} = 0.85$

$C_N = \text{net pressure coefficient, for angle of plane of roof from horizontal, } \theta = 12^\circ, \text{ the values of } C_{NW} = 1.1 \text{ and } C_{NL} = -0.36$

Two 12-degree slopes of the gable roof ($\theta = 12^\circ$) for this case and the effective solar panel area of $12.59 \text{ m}^2$ were considered to determine the total traction acting on the structure.

3.2. Computational fluid dynamics
Computational fluid dynamics (CFD) is another engineering tool that can be used for the prediction of the traction from the aerodynamic characteristics of the platform in this section. The typical size for a set was 4 meters by 6 meters and the depth was 0.77 meters (Fig.4). The computational domain and the model disregarding the sunken part are presented as illustrated in Fig.5.

![Fig. 4: Dimension of a solar floating platform set](image1)

![Fig. 5: Computational domain of the analysis](image2)

3.3. Wind-tunnel testing
A conceptual and preliminary study was undertaken concerning the experimental design before fabricating the models and other components. The size of the test section, wind speed, depth of water, ramp angle for smooth flow, and load cell specification are affected by the characteristic of the solar floating system under wind conditions and diagnostic instrumentation. CFD analysis played an important role in this early stage. Fig.6 shows the dimensions of the designed water tray that was fixed at $2.06 \text{ m} \times 0.81 \text{ m}$ to fit with the test section of the tunnel (Fig.6). These dimensions also included a ramp for making the flow as smooth as possible.
The model and other components for wind tunnel testing studied were: ramp slope, wind speed, water depth and, especially the arrangement of the solar floating platform. All parameters had to allow for the load cell capability and for the traction to be measured. The study found that the 1:20 scaled platform was suitable for testing in a wind tunnel. A water tray including a ramp with an angle of 15 degrees was appropriate to provide a smooth flow. A single set of the solar floating platform (the 1 x 1 model) resulted in too little traction to be measured by the existing load cell. Therefore, a group of scaled models with an arrangement of 2 x 2 was used to increase the measured drag force approximated by the CFD analysis within the load cell limitation (Fig.7). Moreover, the analytical closed form equation could not be used to determine the drag force on the 2 x 2 model and so the drag forces were measured directly using a load cell connected to a special adaptor which was designed for this test purpose as shown in Fig.7. The preliminary study using CFD indicated that the wind direction approaching the platform could have a significant influence on traction. Consequently, wind speeds of 5, 7, 9, and 11 m/s were used for the test using both a side (Fig.8) and front (Fig.9) wind direction.
Fig. 8: Testing the 2 x 2 model with side wind direction

Fig. 9: Testing the 2 x 2 model with front wind direction

4. Results and discussions
The normal pressure on the gable roof was calculated using eq. (1) and (2). The calculation was performed for an open structure representing a single set of the solar floating platform or the 1 x 1 arrangement according to ASCE7-10. It was found that normal pressure exhibited in Fig.10 was not equal to the windward and leeward halves of the roof surface. When the wind came from the left side, the windward roof facing the wind first had higher normal pressure than the other roof. According to eq. (2), the normal pressure acting on the left and right roofs was 557 N/m² and 203 N/m², respectively, indicating that the resultant traction from the closed form equations of a single platform under 120 km/h (33.33 m/s) was 1,936.71 N.

Fig. 10: Pressure acting on gable roof of an open building resulting in traction on the 1 x 1 platform

Using CFD, the mathematical model of a single platform, the 1 x 1 model without sunken parts, was analyzed with an inlet velocity of 120 km/h (33.33 m/s) which was the same condition used in the closed form analysis. The mesh of the model was generated as represented in Fig.11. Simulation was
used to extract the drag force exerted on the model. The total drag force acting on the entire surface area of the model by the resultant force in the flow direction was 2,153.27 N.

![Fig. 11: Mesh of the 1 x 1 model](image1)

Based on the CFD simulation results, the speed in a given wind direction of the air throughout the model is demonstrated in Fig. 12. It indicates that the windward roof directly confronts the flow while the flow is separated on the leeward roof. This study confirmed a similar trend to the traction obtained from the closed form analysis.

![Fig. 12: Velocity display within the computational domain](image2)

The results of the 3 evaluation methods for the case of the 1x1 platform for both the closed form analytical equation and the CFD are shown in Table 1. The difference between the 2 cases was approximately 10%. The traction obtained from the standard was less than from the CFD analysis probably due to the standard taking only the roof into account while the CFD analysis considered the whole floating part in the mathematical model. These results show the prediction of the traction was within the range of 1,900 N to 2,200 N which is a good beginning for drawing a set of solar floating platforms on a water surface. The results indicated that the traction was greater in the CFD result than the standard. It is preferable to rely on the value from CFD analysis.

| Table 1: Difference between traction obtained from the ASCE 7-10 standard and CFD analysis for a solar floating platform set |
|---------------------------------|-----------------|-----------------|
| ASCE 7-10                       | CFD             | % Difference    |
| 1,936.71 N                      | 2,153.27 N      | 10.06           |

The traction was estimated using CFD analysis of a mathematical model developed during previous study. The model was simulated only for a single unit of the solar floating platform. In this case, a group of 2 x 2 pattern had been tested in the wind tunnel to compare the traction obtained from CFD analysis.

This work developed a mathematical model, including the floating part of the 2 x 2 pattern of a 1:20 scaled model, a water tray with a ramp containing water of a fixed depth. The sunken part of the scaled model was calculated using static equilibrium. Two wind directions were studied: side and front. The simulation was run with air speeds of 5, 7, and 9 m/s. There were problems associated with using the 1:20 scaled model, including difficulty in making the model float in a realistic manner and because of the scaling, with-standing wind speeds greater than 9 m/s. Following the failure due to diverging oscillation in the wind tunnel caused by the instability, it was only possible to test using 5, 7, and 9 m/s for comparison with the CFD simulation. The experiment was conducted in the low speed wind tunnel at the Department of Aerospace Engineering, Kasetsart University, Bangkok, Thailand.

Flow trajectories over the model with an air speed of 7 m/s to the side direction are shown in Fig. 13. It can be seen that the velocity increased as the air collided with the ramp. Subsequently, the
velocity gradually increased to the top of the ramp. At the same time, the velocity directly behind the ramp dropped substantially to approximately 4 m/s. This velocity accelerated to 9 m/s when the air flowed over the windward roof of the 2 x 2 scaled platform. The air speed substantially decreased over the leeward roof. After this point, the air speed was forced to increase over the next gable roof, whose inclined slope was the same as the windward roof. However, the air speed at the top of the second gable was lower than for the first. This indicates that the kinetic energy of the wind can be dissipated when the air stream faced the first gable. For groups of several sets of solar floating platforms, it is possible to reduce wind resistance by installation of solar floating sets close behind each other.

**Fig. 13**: Flow trajectories of the 2 x 2 pattern of 1:20 scaled model

The averaged results of the CFD simulations versus the wind-tunnel measurement are presented in Table 2 for the 2 x 2 pattern of the 1:20 scaled model. The side wind direction had more influence on the traction than the front wind direction. It was clear that these results yielded from the frontal area of the model in both cases. The trend line can be obtained by using the quadratic equation shown in Fig.14.

**Table 2**: Comparison of traction obtained from CFD simulations versus wind-tunnel measurement for the 2 x 2 pattern of 1:20 scaled model

| Velocity (m/s) | Side wind direction | Front wind direction (N) |
|---------------|---------------------|-------------------------|
|               | CFD-Side            | WT-Side                 | CFD-Front | WT-Front |
| 5             | 0.14                | 0.17                    | 0.10      | 0.12     |
| 7             | 0.26                | 0.29                    | 0.15      | 0.27     |
| 9             | 0.44                | 0.46                    | 0.25      | 0.38     |

**Fig. 14**: Comparison of traction results from side and front wind directions
For a side wind direction, there was good agreement between the experimental and simulation results. For a front wind direction, the results indicated that increasing the wind speed could generate greater traction as was observed during the tests carried out. It was noted that the scaled platform could easily vibrate on the water due to wind and waves. When the wind speed increased, the waves oscillated up and down with a higher amplitude. This motion induced instability in the whole platform, especially, forming an angle of attack which had a large effect on the traction.

5. Conclusion

The agreement between the CFD analysis and the wind tunnel measurements was considered good, which could support using these simulations for further analysis of the flow field and also using the same computational models for the CFD analysis of groups of on-site platforms. In this case, a group of 9 x 28 and 28 x 9 pattern was used on site. It was not possible to generate a mathematical model of the 252 units in the computational domain due to the time required.

The study results showed that the CFD model used was confirmed by both the close form equation and the experimental model. By using the CFD model, the research was expanded into a full scaled analysis of an N x M arrangement and could summarize the traction equation as a function of the pattern of the platform as follows:

\[ D(N, M) = 2075.8N^{0.6532}M^{0.9052} \]  \hspace{1cm} (3)

for a wind speed of 120 km/hr (33.33 m/s)

and

\[ D(N, M, V) = K_v(V)\ 2075.8N^{0.6532}M^{0.9052} \]  \hspace{1cm} (4)

where

\[ K_v(V) = (0.019564618 + 0.007704667V) / (1 - 0.0004656279V) \]

\[ D = \text{drag or traction force (newton)} \]
\[ N = \text{number of platforms in a column} \]
\[ M = \text{number of platforms in a row} \]
\[ V = \text{wind speed (km/h)} \]

Further study is needed on the vibration effect on several sets of the solar floating platform. In addition, traction might be reduced by the installation of each solar floating set at a separation distance using the CFD analysis.

Acknowledgement

The authors thank Kampot Cement Co., Ltd. for supporting this research and making the learning experience possible through the grant reference no.7010161755 to the Design Clinic Research Unit (DSCN), Department of Aerospace Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand.

References

[1] Nelson S. Physical Geology, Energy Resources: Tulane University 2015. available online: https://www.tulane.edu/~sanelson/eens1110/energy.htm, last visit:08.02.2019.
[2] World Energy Council. World Energy Resources: Hydro 2013. available online: https://www.worldenergy.org/wp-content/uploads/2013/10/WER_2013_5_Hydro.pdf, last visit:08.02.2019.
[3] Urban F & Mitchell T. Climate change, disasters and electricity generation. Institute of Development Studies IDS 2011.
[4] Choi Y-K. A Study on Power Generation Analysis of Floating PV System. International Journal
of Software Engineering and its Applications 2014; Vol.8 (1):75-84. doi: 10.14257/ijseia.2014.8.1.07

[5] World Meteorological Organization Technical Document. Typhoon Committee Operational Manual: Meteorological Component 2015. Tropical Cyclon Programme, Report No. TCP-23.

[6] Jompuk K, Triyakun N, Bunyawanichakul P & Siribodhi P. Drag Analysis of Solar Floating under Aerodynamic Load. Proceedings of the 32nd Conference of Mechanical Engineering Network of Thailand 2018.

[7] Pornvoraphat P, Triyakum N, Bunyawanichakul P & Siribodhi P. Lift Analysis of Solar Floating under Aerodynamic Load. Proceedings of the 32nd Conference of Mechanical Engineering Network of Thailand 2018.

[8] American Society of Civil Engineers. Minimum Design Loads for Buildings and Other Structures. Structural Engineering Institute 2010:250-262.