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Micro Wave Energy Farming on Slender Pile Structure

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ABSTRACT
The development of renewable energy technology has mostly been focused on macro-sized farming models. Recent studies have explored the benefits of micro wave energy to support offshore sensor networks. This paper discusses the viability of micro ocean energy farming of wave energy on slender pile structure through piezoelectric converters. Case study was obtained using Tuban environmental data from the year 2004-2009. Significant wave height and period were used to generate wave forces on slender pile and converted to electrical energy using simple piezoelectric converter equations. The resulting wave force on a 0.03m thick piezoelectric plate generates voltage of 0.6 Volt.

Keywords: *micro wave energy, slender pile, piezoelectric converter*

1. INTRODUCTION

Wave energy is one of the most widely researched renewable energy sources attributing to its predictable characteristics. Large scale wave energy farms are already functional [1], and more recently micro wave energy farming, specifically to support unmanned oceanographic monitoring sensors, is being explored [2]. The development of micro wave energy farming is intended to solve the drawbacks of pollution and maintenance downtime for unmanned offshore sensors. Particularly in Indonesia where oceanographic data are commonly collected by coastal stations and research vessels, long-term unmanned data-collecting offshore sensors will facilitate more reliable data collecting in bigger time and space resolutions [3], thereby facilitating engineering designs and government policies regarding environmental issues.

The usage of piezoelectric converter perfectly accommodates limitations imposed by the factor of size, dimensions, and weight of offshore sensors [2]. Piezoelectric converters are flexible in dimensions and very lightweight, especially compared to other methods of energy farming conventionally used for commercial-scale wave energy farms. Solar-powered sensor buoys have been studied, but the use of piezoelectric converters will allow more flexibility in sensor design, operability, and cuts maintenance downtime.

There are various piezoelectric materials with a range of electric permissivity and stiffness of material. These must be examined at each case study to determine the optimum design for energy generation.

2. MATERIALS AND METHODS

The flow and procedure of study was conducted as follows. Firstly, literature review was conducted by referring to available texts and codes. This stage also consists of acquiring environmental case data to be processed. The collected wind data was then analyzed to generate wind waves using hindcasting method. To simulate wave propagation to Tuban beach, resulting wave parameters were calculated according to wave shoaling and refraction equations through relevant bathymetry levels. Wave forces were then calculated using Morison's wave force equations, and then converted to electrical energy using known piezoelectric equations [4].

2.1 Data Collection

The data collection comprised of secondary observation from local meteorological station at Tuban, East Java, as well as bathymetry image of Tuban coast from GEBCO imaging.

Aside from environmental data, publications on various piezoelectric materials were put into consideration for appropriate case study material.

2.2 Data Analysis

Wind and fetch distance were analyzed to obtain deep-water wave characteristics. Fetch method used to convert wind direction and duration into wave characteristics are

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performed according to US Army Engineers [5].

2.3 Wave Analysis

The resulting deep-water wave characteristics were used to obtain wave characteristics at the determined location using wave shoaling and refraction equations. Using common pile sizes, wave force on structure was calculated according to Morison's equation on wave forces on fixed slender structure.

We determine the arbitrary location at a distance of 40m from Tuban shoreline, shown in red line in Fig. 1. The seafloor depth according to existing bathymetry measurement is 5m.

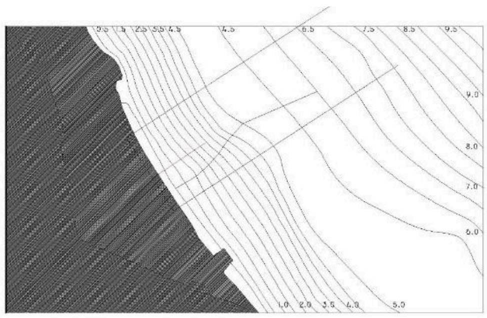

Figure 1. Tuban bathymetry

2.4 Energy Conversion

Wave forces were converted according to piezoelectric equations for voltage generation and capacitance for set material thickness [6]. The properties of piezoelectric materials are obtained from past research publications, which are[7, 8]:

Table 1. Piezoelectric materials properties

Material	PZT-5A	Silicon	
Thickness	0.03	0.03	m
Surface Area	0.785	0.785	m^2
Strain Coefficient	1.6×10^{-10}	2.2×10^{-10}	C/N
Relative Dielectric Const.	2100	8	

An in-scale schematic of the case study is as follows:

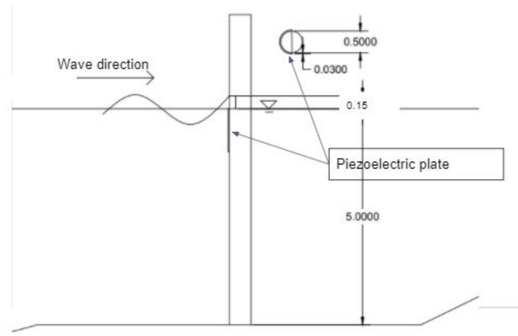

Figure 2. In-scale case study illustration

The structure is fixed at depth of 5m with diameter of 0.5m, with piezoelectric layer spray painted at the side facing wave direction.

3. RESULTS AND DISCUSSION

3.1 Environment Data

Analysis on wind data during 2004-2009 period yielded the following results:

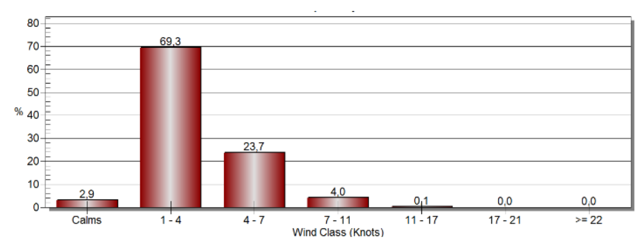

Figure 3. Wind class frequency distribution 2004-2009

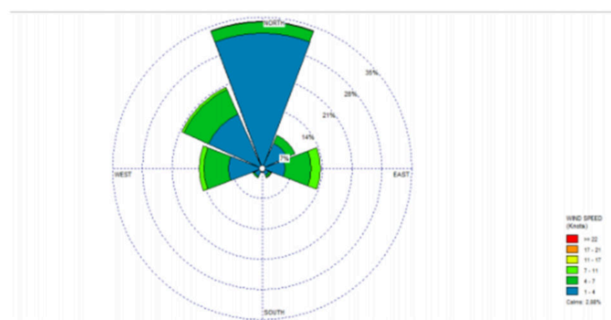

Figure 4. Wind direction distribution 2004-2009

It can be seen from the graphs that the dominant wind direction blowing to Tuban is from the north direction (35%) at the speeds of 1-4 knots (69.3%). Further calculations are commenced using dominant wind direction and speeds using the fetch method, first by converting land wind speed to sea surface wind speed, factoring surface tension coefficient and wind blowing distance, to calculate the generated wind-wave.

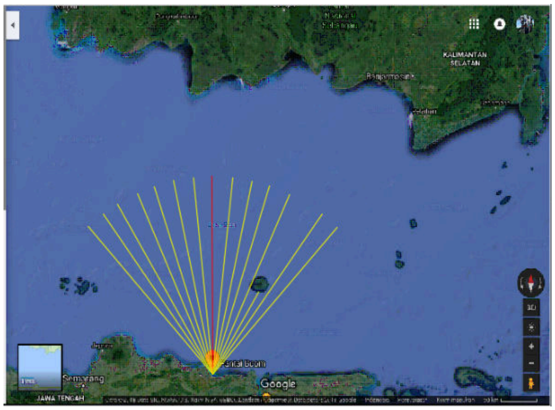

Figure 5. Tuban beach fetch distances

Table 2. Fetch Calculation

θ	Cos θ	Xᵢ (Km)	Xi cos θ
-42	0.74	9.72	7.22
-36	0.81	250	202.25
-30	0.87	250	216.51
-24	0.91	250	228.39
-18	0.95	250	237.76
-12	0.98	250	244.54
-6	0.99	250	248.63
0	1.0	250	250
6	0.99	250	248.63
12	0.98	250	244.54
18	0.95	250	237.76
24	0.91	250	228.39
30	0.87	121.41	105.14
36	0.81	250	202.25
42	0.74	250	185.79
Σ			3087.8
F_{EFF}	228.54	Km	

The final calculated effective fetch distance at Tuban beach is 228.54 kilometers.

3.2 Wave Generation

Wind-wave generated by dominant wind speed over fetch distance is calculated using tables according to [5]. The wave statistics are then calculated according to wave shoaling & refraction principles to obtain wave parameters at the designated location.

Table 3. Wave parameters at water depth of 5m

Parameter		unit
Significant wave height	0.303	m
Significant wave period	4.3	s
Significant wave length	29	m

3.3 Wave Analysis

Wave force on unit length of fixed slender structure according to Morison's equations are:

$$F_T = F_I + F_D \tag{1}$$

$$F_D = \frac{1}{2}\rho C_D A\left|U_{x,z}\right| \tag{2}$$

$$F_{Ix,y} = F_{Px,z} + F_{Ax,z} \tag{3}$$

$$F_{Ax,z} = \rho C_{Mx,z}\alpha_{x,z}A_s \tag{4}$$

$$F_{Dx,z} = \rho\alpha_{x,z}A_s \tag{5}$$

Where F_T is total forces, F_I is inertial forces, and F_D is frictional forces, C_D is drag coefficient, $|U_{X,Z}|$ is absolute value of particle velocity on the x and z axes, F_P is dynamic pressure, F_A is acceleration force, C_M is the added mass coefficient, and $\alpha_{x,z}$ is particle horizontal and vertical acceleration through the cross section A_S.

The summary of parameters being used in calculation process can be seen in Table 4.

Table 4. Wave & structure parameters

Wave amplitude	0.1515	m
Water depth	5	m
Wave celerity	1.7241	m/s
Diameter	0.5	M
Drag coefficient	1.2	
Added mass coeff.	2	
Seawater density	1.025	T/m^3
Reynolds no.	1985.6	

The calculations yielded wave forces as follows:

Table 5. Wave forces on structure

θ (rad)	fI	fD	fT	t (sec)
0.0000	-5.78668	0.00000	-5.78668	0.00
0.3142	-5.50346	0.04264	-5.46082	0.20
0.6283	-4.68152	0.15426	-4.52726	0.40
0.9425	-3.40132	0.29223	-3.10909	0.60
1.2566	-1.78818	0.40385	-1.38433	0.80
1.5708	0.00000	0.44649	0.44649	1.00
1.8850	1.78818	0.40385	2.19204	1.20
2.1991	3.40132	0.29223	3.69355	1.40
2.5133	4.68152	0.15426	4.83578	1.60
2.8274	5.50346	0.04264	5.54609	1.80
3.1416	5.78668	0.00000	5.78668	2.00
3.4558	5.50346	-0.04264	5.46082	2.20
3.7699	4.68152	-0.15426	4.52726	2.40
4.0841	3.40132	-0.29223	3.10909	2.60

4.3982	1.78818	-0.40385	1.38433	2.80
4.7124	0.00000	-0.44649	-0.44649	3.00
5.0265	-1.78818	-0.40385	-2.19204	3.20
5.3407	-3.40132	-0.29223	-3.69355	3.40
5.6549	-4.68152	-0.15426	-4.83578	3.60
5.9690	-5.50346	-0.04264	-5.54609	3.80
6.2832	-5.78668	0.00000	-5.78668	4.00
6.5973	-5.50346	0.04264	-5.46082	4.20
6.9115	-4.68152	0.15426	-4.52726	4.40
7.2257	-3.40132	0.29223	-3.10909	4.60
7.5398	-1.78818	0.40385	-1.38433	4.80
7.8540	0.00000	0.44649	0.44649	5.00
8.1681	1.78818	0.40385	2.19204	5.20
8.4823	3.40132	0.29223	3.69355	5.40
8.7965	4.68152	0.15426	4.83578	5.60
9.1106	5.50346	0.04264	5.54609	5.80
9.4248	5.78668	0.00000	5.78668	6.00
9.7389	5.50346	-0.04264	5.46082	6.20
10.0531	4.68152	-0.15426	4.52726	6.40
10.3673	3.40132	-0.29223	3.10909	6.60
10.6814	1.78818	-0.40385	1.38433	6.80
10.9956	0.00000	-0.44649	-0.44649	7.00
11.3097	-1.78818	-0.40385	-2.19204	7.20
11.6239	-3.40132	-0.29223	-3.69355	7.40
11.9381	-4.68152	-0.15426	-4.83578	7.60
12.2522	-5.50346	-0.04264	-5.54609	7.80
12.5664	-5.78668	0.00000	-5.78668	8.00

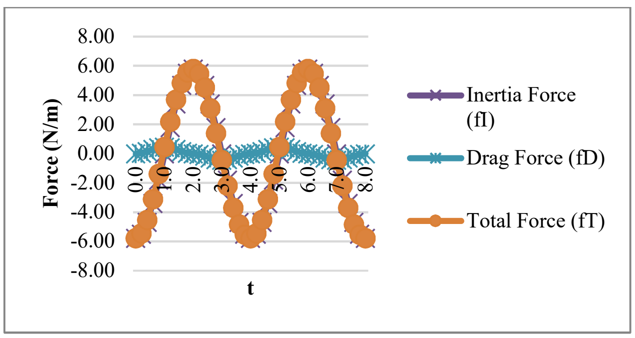

Figure 5. Wave forces on structure

It is apparent that maximum wave force amplitude is at 6 N/m. Drag force is relatively negligible compared to inertial force at a magnitude of 0.4 N/m. It should be noted that these equations are forces resulting from interaction of wave particles with slender pile, with direction normal to pile surface area. Each unit length of the pile submerged underwater will have the same interactive force irrelevant of its relative depth.

3.4 Energy Conversion

The resultant wave forces are converted into electrical energy in terms of voltage generated by a piezoelectric unit with the specified dimensions and materials. The governing equation is

$$U = \frac{Q}{C} = \frac{hd_{33}F}{\varepsilon_r \varepsilon_0 S} \qquad (6)$$

Where U is output voltage in volts, Q is the generated charge in Coulomb, C is capacitance, **F** is excitation force, d_{33} is piezoelectric transversal charge coefficient, while ε_0 and ε_r are absolute and relative dielectric constant of the piezoelectric materials [6]. In order to determine ideal piezoelectric material for ocean energy farming, the calculations were performed under assumption that both piezoelectric materials are of same dimensions. The actual ideal thickness of material as well as maximum generated electricity for each material depends on material stiffness, which is not considered in this paper [9].

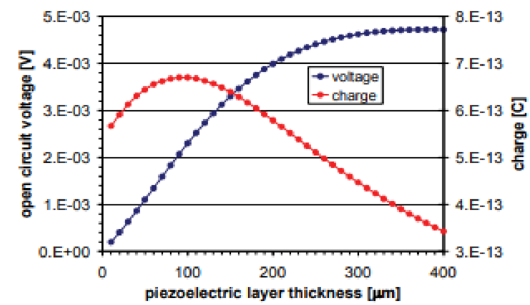

Figure 6. Voltage and charge as function of piezo thickness

Results of the calculations are as follows:

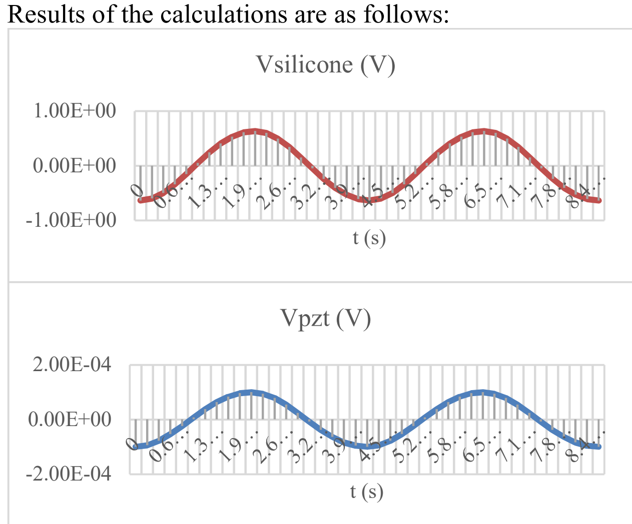

Figure 7. Output voltage on silicone & PZT ceramic piezoelectric units, respectively

The maximum output voltage of silicone based piezoelectric plate is 0.6 volt, while PZT ceramic plate yields 9.9 10^{-5} volt. From this result it can be seen that silicone composite piezoelectric is more appropriate for use in wave energy farming.

4. CASE STUDY

An unmanned, automatic ultrasonic tide gauge design powered by solar panels was researched in [10]. The microchip and GSM module used in design are specified in Table 6.

Table 6. Ultrasonic tide gauge specification

Operational voltage	5V
Recommended input voltage	7-12V
Voltage limit	6-20V

The principles of piezoelectricity means the current generated by piezoelectric generator is AC current. The tide gauge uses DC current, which requires the use of current rectifier.

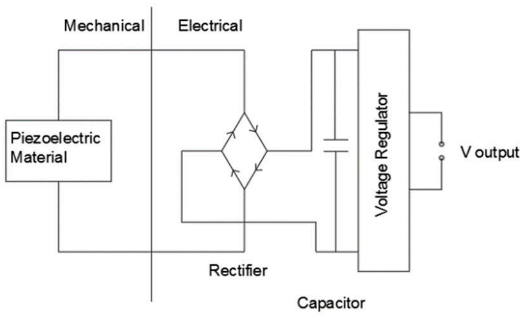

Figure 8. A circuit of piezoelectric converter with rectifier

For ease of calculation, resistance and heat loss will be ignored, as well as operational voltage of the voltage rectifier and regulator. Using the discussed piezoelectric materials and dimensions, a theoretical tide gauge set up in the designated location would need to be powered by 10 units of the piezoelectric converter in order to satisfy the voltage input limit of 6V.

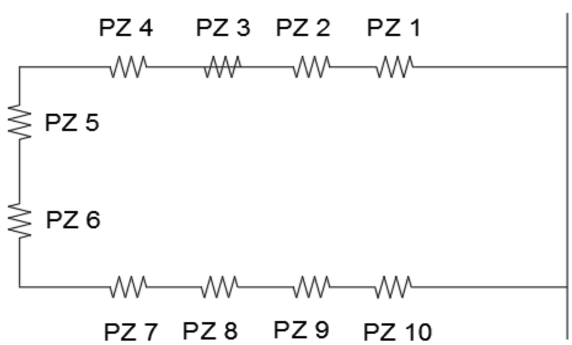

Figure 9. Array of piezoelectric converters in a series circuit

Where PZ 1, 2, 3, and so on are piezoelectric plates arranged in a series according to the Ohm Law.

$$V_T = V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + \cdots + V_n \qquad (7)$$

From this number, at depth of 5m there is not enough section of the single pile submerged to satisfy the energy requirements. Each unit length of the structure can accommodate a unit of piezoelectric converter, meaning at depth of 5m, at maximum there can be 5 units of converter. This requires another structure with 5 converters located adjacent and connected serially to supply power, or the use of amplifiers (which is not considered in this paper).

5. CONCLUSIONS

From calculations and analysis we can conclude that

1. Waves in Tuban beach at water depth of 5m have significant wave height of 0.303 m and period of 4s. The Morison forces acting on 0.5 m diameter slender pile from these waves are 6N, at maximum.
2. The force converted using PZT piezoelectric converter generated 9.99 10^{-5} volt of electricity, while silicone piezoelectric generated 0.6 volt.

We have concluded that silicone piezoelectric is the optimal type of piezoelectric material with regards to smaller environmental loads exhibited by Tuban beach. A case study using an experimental tide gauge design has been calculated.

Further research using physical model of wave conditions to better represent actual wave conditions must be conducted, as well as physical converters, to account for conversion efficiency. Furthermore, practical usage of small wave amplitudes necessitate the use of amplifier and voltage regulator that has not been considered in this paper. Both of which are essential parts of implementing micro energy farming.

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