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RESEARCH ARTICLE

Simulation of offshore aquaculture system for macro algae (seaweed) oceanic farming

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ABSTRACT
Large-scale cultivation of seaweed has become one of the most important aquaculture activities in Malaysia which may help increase farmers' incomes as well as seaweed itself can be processed into many beneficial end products. The present location of seaweed farming selected by farmers is situated close proximity to the coastline which is between 100 and 200 m from the seashore. The unfavourable condition of sea during rough sea with high wave and high speed of current is always a problem to the farmers since this environmental condition destroys their seaweed planting lines. To avoid the above problem, especially in monsoon prone area, a thorough analysis needs to be done in order to prevent environmental load from destroying seaweed platform on its mooring line when subjected to greater stress. The main objective of this study is to perform a simulation study which will allow analysis of the best mooring system for multi-body floating seaweed farm, together with understanding of the reliability and effectiveness of the system. This paper presents the design of seaweed platform model with mooring assessment in order to obtain a comprehensive and reliable seaweed mooring platform with the aid of mooring simulation software and model tests.

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offshore aquaculture system; seaweed platform; mooring assessment; environmental load

Introduction

Seaweed has become one of the valuable resources on earth that contains many benefits for human being and also many applications across a range of industrial sectors. Seaweed is categorised as macro algae which are sometimes called "good kinds of algae". The use of seaweed has been widely recognised in cosmetics, health products, horticulture, food industries, biofuel production, etc (Olanrewaju et al. 2015a, 2015b). Due to these unique characteristics and their functions, governments nowadays have done many efforts to increase the production of seaweed per year (Crawford 2002).

Seaweed farming in Malaysia had started since year 1978 until now. Sabah is the only seaweed-producing state. Sabah has become the major producer in this sector and it has been widely operated in Semporna, Lahad Datu, Kudat and Kunak by focusing on two types of seaweed species which are *Kappaphycus alverezii sp.* and *Eucheuma spinosium sp.* (Olanrewaju et al. 2015c). Recently, Malaysia seaweed industry has targeted to produce 150,000 metric tons of high quality processed seaweed which is worth RM 1.45 billion by the year 2020. A discussion in "Bio-Borneo Conference 2013" summarised that the production of seaweed farming sector will not be in small-scale anymore as there are many efforts in increasing and expanding the locations to 50,000–100,000 hectares to produce an estimate of 200,000–300,000 tons annually with the aid of more organic, systematic and dedicated productive farms.

The necessity of seaweed farming using floating structural concept is very important nowadays as a result of limited space near the ocean shoreline (Sakthivel 2005). This may help increase in seaweed production and thus seaweed farmers' wages. With advancement in computer technology and the aging of many critical structures such as buildings, bridges, underground pipelines, offshore structures, hurricane protection barriers, mechanical structures, etc., renewed efforts can be seen in the area of structural simulation, design and assessment (Mahmoodian et al. 2012; Fang et al. 2013; Tee et al. 2013; Shi and Tee 2014). The use of new and modern technology to create seaweed farming is essential to seaweed farmers or fishermen for the improvement of seaweed cultivation with the objective to protect oceanic environment from any damage which could impose risk to the production of seaweed.

According to Sade et al. (2006), apart from using floating structural type farm, a systematic and reliable mooring system is required to withstand from any unexpected uncapped weather and ocean conditions (Sakthivel 2007; Kvitrud 2014; Mousavi and Gardoni 2014). Thus, the main objective of this study is to perform a simulation study which will allow analysis of the best mooring system for multi-body floating seaweed farm, together with understanding of the reliability and effectiveness of the system. In this study, Ariane 7 software is used to simulate large floating structures for seaweed farming.

Offshore aquaculture with its mooring system

Offshore aquaculture is also generally known as an open ocean aquaculture. This is a novel approach to mariculture or marine farming of aquatic plant and fish farms where they are deployed at some distance offshore (Sturrock et al. 2008). Seaweed farming has grown significantly around the world over the last two decades. Its grow cycle is short which only takes between 2 and 3 months and it depends on the types of seaweed. Because of its potential and its function that can be used in many areas, many developing countries have taken part in this new type of

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socio-economic activity. According to Valderama (2012), a lot of countries have involved in this seaweed aquaculture sector such as in Asia (Philippines, Indonesia, and India), Africa (Tanzania), Oceania (Solomon Islands) and Latin America (Mexico).

The design of offshore farms is required to withstand any external forces that are acting on them in order to maintain their functionality while protect the organisms in them (Andrianov 2005; Koekoek 2010). Naylor and Bruke (2005) suggest that the farms that built at the offshore environment should be sturdier than the inshore and are able to resist the high energy from ocean currents.

Mooring system is required in order to hold floating platforms such as cages or aquaculture farms against the available external forces (Zhao et al. 2012; Yang et al. 2014; Cifuentes and Kim 2015; Pan et al. 2016). These external forces are mainly comprised of wind, current and wave. The importance of mooring is to ensure that the cultivated organisms, cages and nets have the best chance of survival. A recommendation for the mooring system published by American Petroleum Institute (1996) (API RP 2SK) states that, the mooring systems is widely used in station keeping of floating platforms or vessels whether in static or mobile condition. Types of mooring system and its arrangement mainly depend on these factors (Det Norske Veritas 2009): (1) material and design/type of the floating platform, (2) environmental condition/criteria, (3) size and number of cage/farm.

These three factors are important to be able to create a station keeping system for floating structure (DeHondt and Knapp 2008). Apart from the mooring system, a station keeping system also comes with other components altogether in order to fix a floating platform in its position. These components are anchors, mooring lines, mooring buoys, steel plates and rings, shackles, swivels, thimbles, chains, lights, and navigation buoys (Sincock and Sondhi 1993).

The design of very large floating multi-body must be considered in order to prevent any damage to the system and also the surrounding environment (Chakrabarti 2008; Konovessis et al. 2014). According to Watanabe et al. (2004), the designed offshore structures must be able to comply with serviceability and safety requirements for service life of 100 years or more. Safety is an important factor for any design consideration so that there are no ultimate consequences such as environmental damage, fatality and also property destruction (Det Norske Veritas 1985).

The rules and guidelines of offshore units are discussed in NR 445 (Bureau Veritas 2010). According to NR445, it is divided into four parts: (1) classification and survey (2) structural safety (3) facilities and (4) service notations. Rules regarding mooring systems are presented in NI 493 (Bureau Veritas 2008).

Environmental load analysis

The selected area for model deployment is at Bidong Island located on coordinate 05’36’828”N 103’03’262”E in Terengganu. This area is selected because of its natural condition of high precipitation rate per year with monsoon season that provides a very extreme seawater environment. The area is suitable to test the model in a very unfavourable condition which will endure sustainability of deployment in most floating-body motions. The data of environmental condition is obtained from the Institute of Oceanography at the University Malaysia Terengganu.

Table 1. Collected environmental condition at Bidong Island (in a month).

Wave height (m)	1.5–2.5
Current speed (m/s)	0.2–1.0
Wind velocity (m/s)	15–25
Max/min tide (m)	Max: 0.16 Min: 3.72
Distance from shore (m)	100

Besides that, other hydrographic data is also obtained from literature review and Malaysian Meteorological Department. The collected data are given in Table 1.

The external loads Fx, Fy and Mz/G are specified in the local axis system. External loads include not only hydrodynamic, mooring, damping, wave drift, wind and current loads, but also other loads of various natures that are liable to contribute in low frequency. According to Ariane theoretical manual (Bureau Veritas 2011), all loads are projected on the axes of the floating structure according to the three following equations:

$$Fx = FHx + FMx + FBx + FDx + FWx + FCx + Fox$$
$$Fy = FHy + FMy + FBy + FDy + FWy + FCy + Foy$$
$$Mz/G = MHz + MMz + MBz + MDz + MWz + MCz + Moz,$$

where the following indices are used to identify the origin of each term: H for hydrodynamic loads; M for mooring loads; B for damping loads; D for wave drift loads; W for wind loads; C for current loads and o for other loads which cannot be negligible (riser, thruster, etc.).

The low frequency response of the moored floating platform is obtained by numerical resolution in the time domain of the vectorial differential equations. At each time step, the six wave frequency motions of the vessel centre of gravity are added to its low frequency position. It is assumed in this process that wave frequency motions are not significantly influenced by the variations of mooring stiffness with low frequency motions. Wave frequency motions are therefore computed for the average mooring stiffness corresponding to the mean position of the floating structure during the storm.

The magnitude of the wind force that acts on the floating multi-body is influenced by the wind velocity (speed to relative direction) and by the projected wind area of the floating multi-body. From the Ariane theoretical manual, the resultant wind forces and yaw moment acting through the centre of the floating multi-body are expressed by the following equations:

$$\text{Longitudinalwindforce}: F_{xw} = 1/2 \cdot C_{xw} \cdot \rho_w \cdot {V_w}^2 \cdot A_e$$
$$\text{Lateralwindforce}: F_{yw} = 1/2 \cdot C_{yw} \cdot \rho_w \cdot {V_w}^2 \cdot A_s$$
$$\text{Windyawmoment}: M_w = 1/2 \cdot C_{xyw} \cdot \rho_w \cdot {V_w}^2 \cdot A_s \cdot \text{LWL},$$

where C_{xw}, C_{yw} *and* C_{xyw} are longitudinal, lateral and yaw wind force drag coefficient, respectively, ρ_w is mass of air density, ${V_w}^2$ is wind velocity, A_e and A_s are longitudinal and lateral projected area of floating structure, respectively, and LWL is the length of water line.

The resultant current forces and yaw moment are expressed by the following equations:

$$\text{Longitudinalcurrentforce}: F_{xc} = 1/2 \cdot \rho_c \cdot {V_c}^2 (c_{xca} \cdot \text{S.B/LWL} + c_{xcb} \cdot A_e)$$
$$\text{Lateralcurrentforce}: F_{yc} = 1/2 \cdot C_{yc} \cdot \rho_c \cdot {V_c}^2 \cdot \text{LWL}^2 \cdot T$$
$$\text{Currentyawmoment}: M_c = 1/2 \cdot C_{xyc} \cdot \rho_c \cdot {V_c}^2 \cdot \text{LWL}^2 \cdot T,$$

where ρ_c is mass of current density, V_c^2 is current velocity, C_{yc} is lateral current drag coefficient, c_{xca} is longitudinal skin friction coefficient, c_{xcb} is longitudinal current drag coefficient, B is beam, T is draft and S is wetted surface area.

Simulation and model test

The proposed design is in rectangular shape which minimises the space consumption and is able to increase the production of seaweed cultivation for a single seaweed farm. The proposed design is able to accommodate 100m X 100m planting block shape. This seaweed farm will be first deploying at the sea which is 200 m from the shore with a seedling of three metric tons. This amount will come from 30 planting lines per block that is 100 kgs per planting line.

Model test is very necessary in order to find valuable information from created model as a replicate of prototype. Small-scale physical modelling of a new concept is extremely worthwhile (Chakrabarti 1998). In this model test experiment, some of the coefficient parameters are required to support the mathematical and simulation analysis. The model test is run separately by parts in a towing tank at the University of Technology Malaysia. A small-scale prototype with dimension of 4 m × 2 m is used to measure the forces. The tests are divided into

(1) drag load test,
(2) dynamic test in order to find any additional mass and damping by using planar motion mechanism,
(3) complete system test,
(4) component test.

Results and discussion

Design comparison

Three types of offshore models with different mooring arrangements are simulated using software Ariane 7 and the best design with less tension on mooring is selected. Once selected, the model will then be tested with different depths at 10m and 100m. The model will also be tested at Bidong Island. Figure 1 shows the three types of preliminary models with different mooring arrangements. Basically, one block of seaweed platform model has four main buoys with two planting lines.

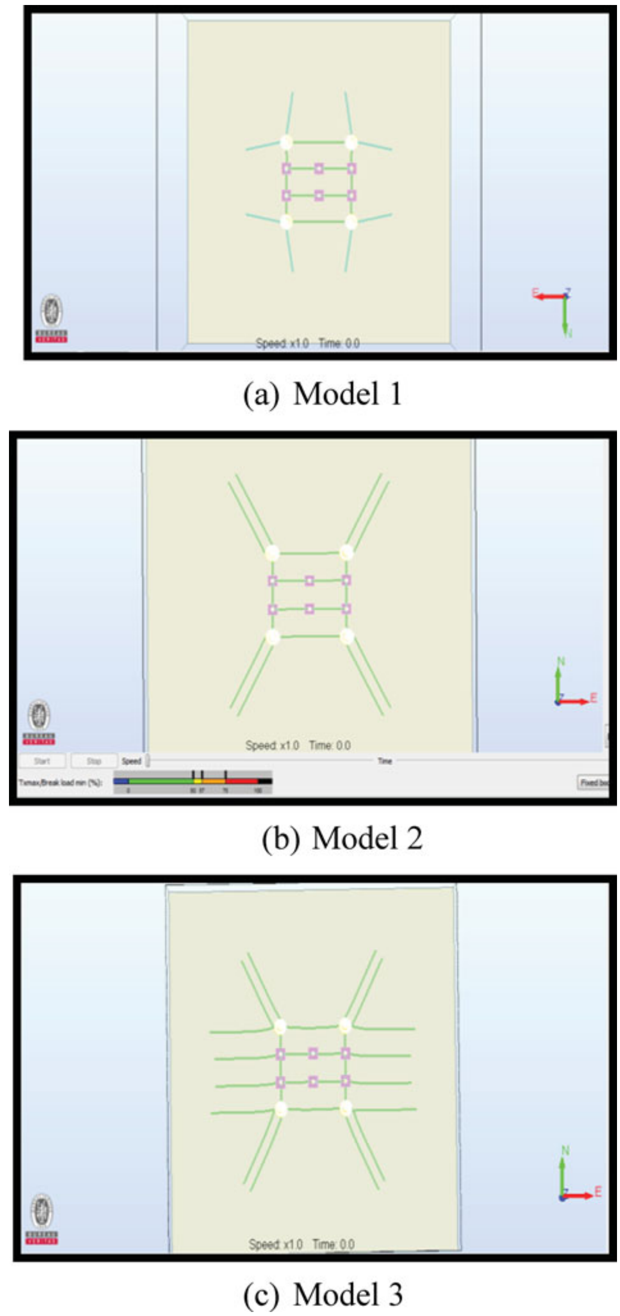

Figure 1. Three types of preliminary models with different mooring arrangements.

Model test analysis in towing tank

Figure 2 shows the result obtained from model test in towing tank. The result is obtained from the towing of one planting line with seaweed at certain speeds and according to selected time period. As shown in Figure 2, three forces at x-, y-, and z-directions are acting when the planting line is dragged in towing tank. The graph is plotted in 60 second time period. The force at z-direction is higher than those at x- and y-directions. The graph shows considerable scatter and is a result of movement of planting line in water which has viscosity that causes resistance to the movement of planting line.

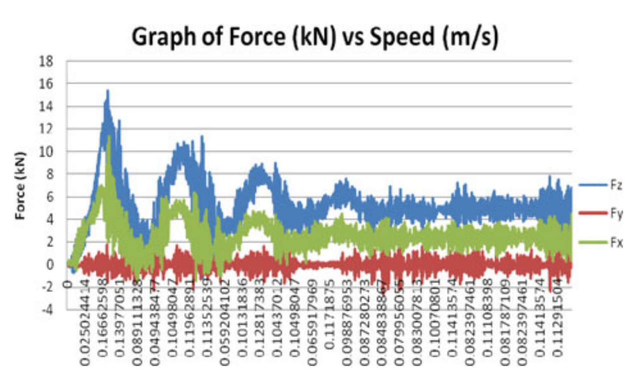

Figure 2. Force vs. speed of planting line from model test analysis.

Time domain simulation

Table 2 shows the parameters involved in time domain simulation of seaweed platform model using software Ariane 7. The time domain simulation is done in duration of 36000 seconds. The environmental load is defined (see next paragraph) and the

Table 2. Parameters involved in time domain simulation.

Duration of simulation (s)	36,000
Time step (s)	1
Recording start time	0
Calculation type	Low frequency
Drift type	Newton approximation
Use current load	Yes
Use wind load	Yes
Use current/wave interaction	Yes
Use thrusters	Yes
Start from initial position	No
Start from equilibrium position	Yes
Block vessel (low-frequency motion)	Yes
External loading routine	No
Relative current	Yes
Relative wind	Yes

Table 3. Parameter values of wave simulation.

Jonswap (wave1)	
Gamma	3.3
Sigma1	0.07
Sigma2	0.09
Significant height (m)	1.5
Modal peak period (s)	10
Min frequency (Hz)	0.015915
Max frequency (Hz)	0.23873
Heading (deg) from north axis clockwise	90
Seed of wave random generator	5
No. of regular Airy waves	200
ITTC (International Towing Tank Conference) (wave2)	
Significant height (m)	1.5
Min frequency (Hz)	0.05
Max frequency (Hz)	0.23873
Heading (deg) from north axis clockwise	90
Seed of wave random generator	5
No. of regular airy waves	200

Table 4. Parameter values of wind simulation.

Harris/DNV (wind)	
Surface drag coefficient k	0.002
Representative length scale L(m)	1800
Mean velocity (m/s)	0.015
Min frequency (Hz)	0.05
Max frequency (Hz)	2
Heading (deg) from north axis clockwise	90
Seed of wave random generator	5
No. of regular airy waves	200

specifications of buoy and installed line are obtained from the manufacturer. In this software, the thruster for buoy is used assuming that the load from seaweed is attached to the planting line. The simulation is done for low-frequency wave between 0.2 and 0.5 Hz.

Tables 3–5 show the environmental parameters for wave, wind and current simulation. Figure 3 shows the environmental loads which act on the seaweed platform during simulation. As shown in Figure 3(a), the wave elevation from two different types of environmental conditions is random due to the low-frequency movement of up-and-down wave amplitude. Similarly, wind load also shows a random force which may be caused by the variation of wind speed from time to time. However, the current load shows a linear graph for both east and north directions. It should be noted that the environmental forces acting on the seaweed platform model differ in wave type but use the same parameters for wind velocity and sea current. The effect of wind

Table 5. Parameter values of current simulation.

Constant (current spectrum)	
Mean velocity (m/s)	0.4
Heading (deg) from north axis clockwise	90

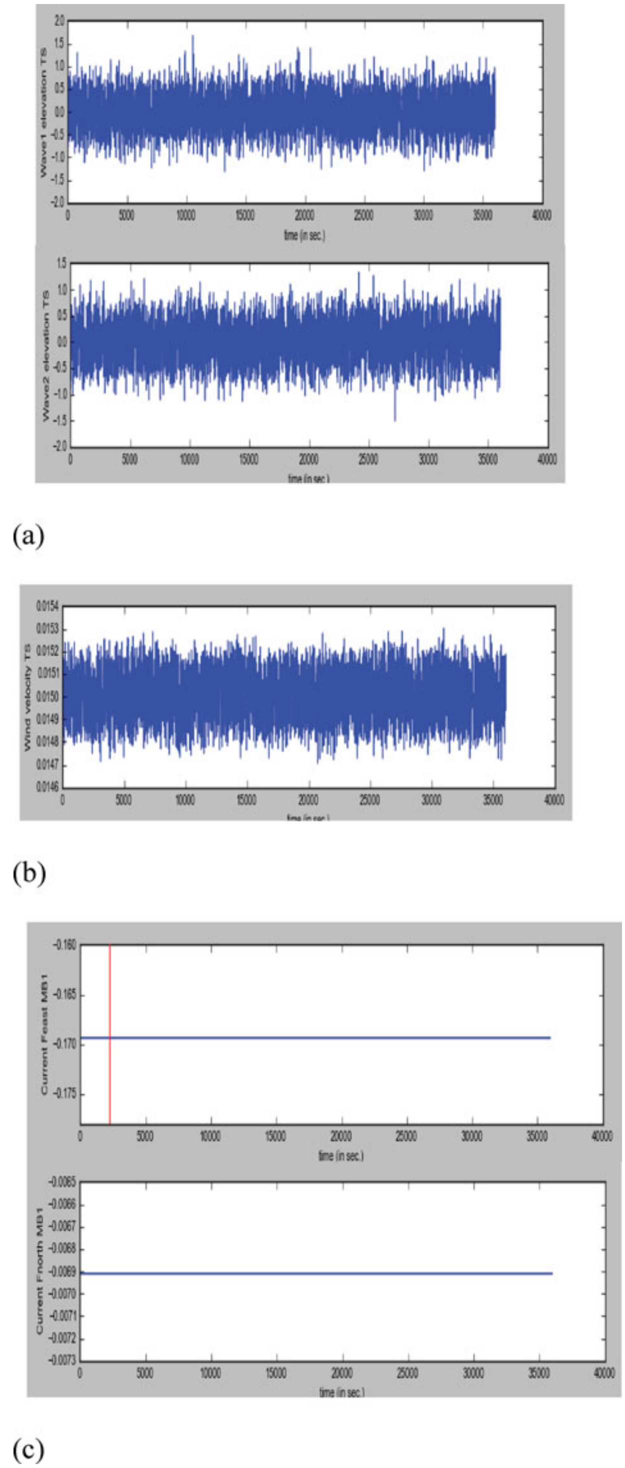

Figure 3. Environmental loads acting on seaweed platform. (a) Wave elevation from 2 types of environments. (b) Wind velocity. (c) Current from north and east directions.

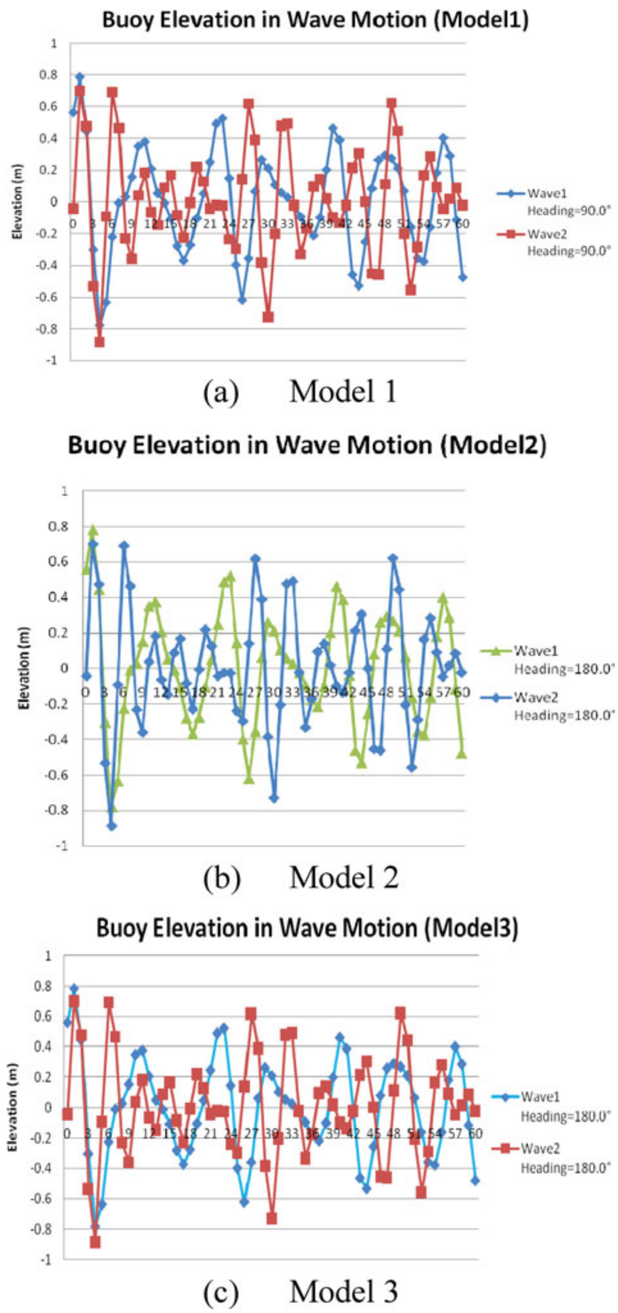

Figure 4. Buoy elevation in wave motion.

load can be negligible as it affects only a little to the seaweed platform model.

Buoy movement and elevation

Figure 4 shows the buoy elevation for three preliminary models subjected to environmental load. Two different wave types are used that are wave1 which is JONSWAP spectrum and wave2 which is recommended by ITTC (International Towing Tank Conference). The selected headings for wave are 90° and 180° of the seaweed platform model. The buoy elevation in wave2 is higher than that in wave1. It is identified that the sinusoidal motion of the buoy is caused by the wave elevation itself. Since the mooring line attached to the buoy has paid out length which is allowable length for the line to extend and retract during up and down motion of buoy. This reduces the tension at connection between mooring line and the buoy during wave elevation motion.

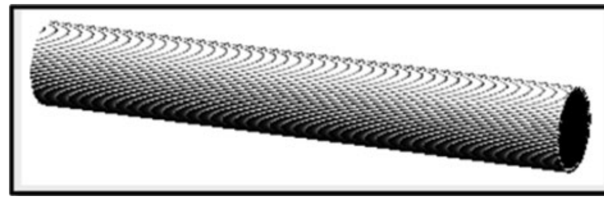

Figure 5. Six-strand wire rope.

Table 6. Parameters of wire rope for seaweed platform model.

Line type	Six-strand wire-rope
Line length (m)	
Mooring line	30
Borderline	15
Planting line	7
Diameter (m)	
Mooring line	0.06
Borderline	0.03
Planting line	0.02
Friction	0.700
Breaking load (kN)	
Mooring line	2448.360
Borderline	830.520
Planting line	418.680

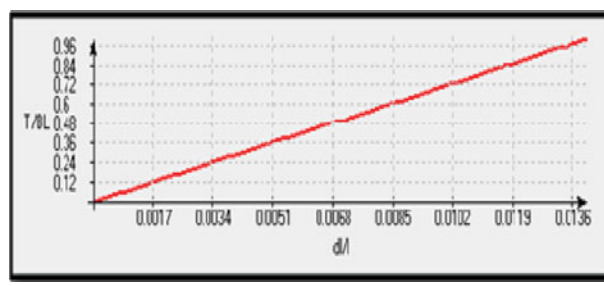

Figure 6. Tension over breaking load versus elongation of the line.

Line profile analysis

The selected line for the seaweed platform model is a six-strand wire rope as shown in Figure 5. The parameters of the wire rope are given in Table 6. The selected type of line is based on the suitability of the floating condition for the seaweed platform model. Figure 6 shows the graph for the tension over breaking load versus elongation of the line. It is observed that the graph is linear proportional when the line elongates. The proportionality constant varies directly as the diameter of the line.

Horizontal and axial tension on mooring line

Figures 7 and 8 show horizontal and axial tension forces of mooring lines at the positions of anchor and fairlead, respectively, for the three preliminary models. The tension forces for these three models are analysed and compared whether they are over the breaking load limit or not. From the parameters shown in Table 6, the breaking load for the mooring lines is given as 2448.36 kN. It is observed that horizontal tension at anchor for model 1 exceeds the line breaking load limit as shown in Figure 7(a). This can be seen at mooring line 2 and mooring

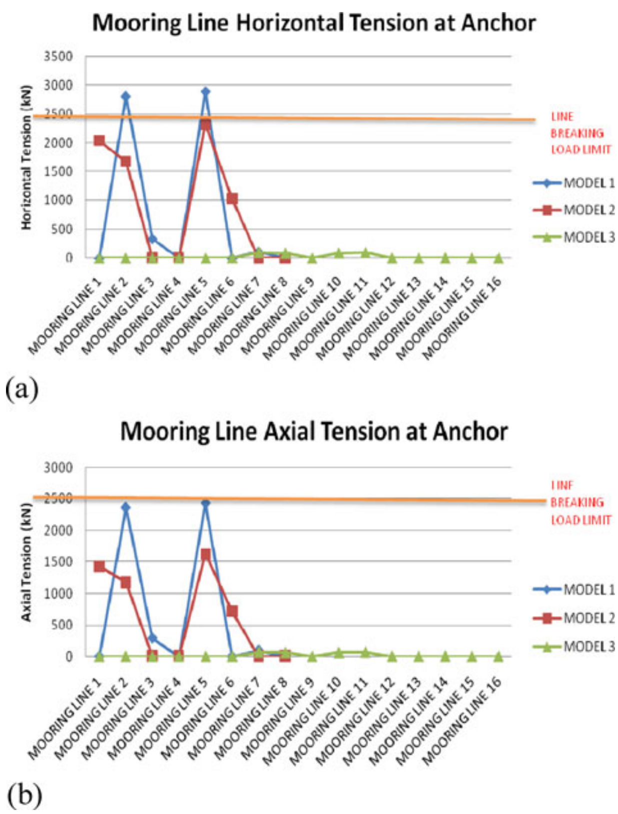

Figure 7. (a) Horizontal tension at anchor. (b) Axial tension at anchor.

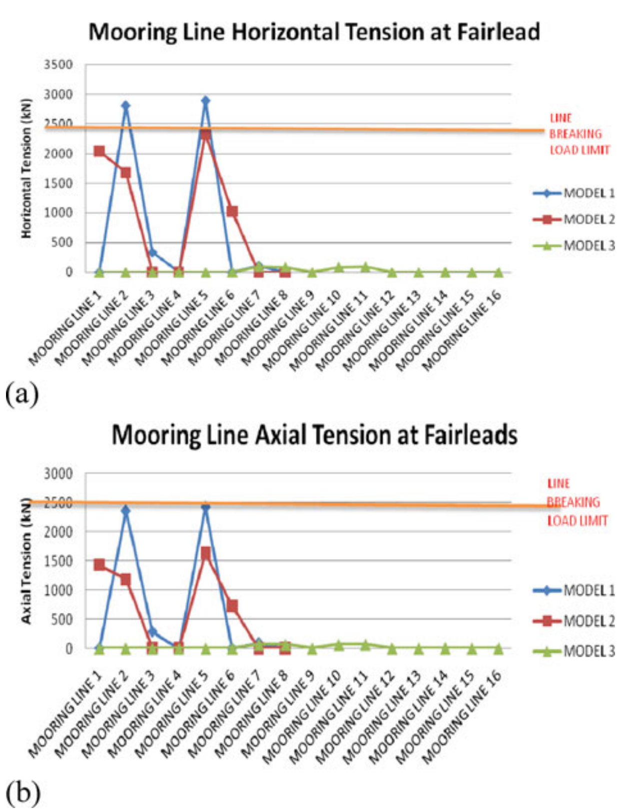

Figure 8. (a) Horizontal tension at fairlead. (b) Axial tension at fairlead.

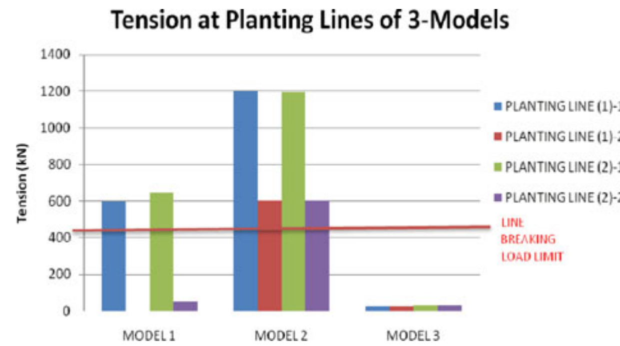

Figure 9. Tension on planting line for three models.

line 5. However, none of the mooring lines for models 2 and 3 have axial and horizontal tension at anchor position above the line breaking load limit. Comparing models 2 and 3, it can be found that horizontal and axial tension forces of mooring lines for model 2 are much higher. Thus, the mooring lines for model 3 have less amount of stress at anchor position than those from the other two seaweed platform models.

Similarly, Figure 8(a) and 8(b) provide the similar observation that horizontal tension forces for model 1 at fairlead position exceed the line breaking load limit at mooring line 2 and mooring line 5. For models 2 and 3, the horizontal tension forces at fairlead position are below the line breaking load limit. On the other hand, it is observed that for the axial tension at fairlead, none of the models have mooring lines which have tension exceed the line breaking load limit. Model 3 has the lowest axial and horizontal tension at fairlead position than those in the other two models.

Tension on planting lines

Figure 9 shows the tension forces exerted on planting lines for the three preliminary models under certain period of time. It is observed that the tension forces on planting lines in models 1 and 2 exceed the planting line breaking load limit. This can be seen that the planting line (1)-1 and planting line (2)-1 have the highest tension during the simulation with environmental load for models 1 and 2. However, none of planting lines in model 3 exceeds the planting line breaking load. The planting lines in model 3 have an average of not more than 100 kN tension force. Thus, the planting lines in model 3 are much more suitable for seaweed farming than those in the other two models.

Animation result of seaweed platform

Figures 11–13 show the animation before and after the time domain simulation for these three preliminary models. Since planting lines have breaking load limit, thus from the animation result, the percentage of exceeding breaking load limit can be represented by colour indicator as shown in Figure 10. Based on the colour indicator, tension forces of lines can be determined from visual observation. For example, green colour is defined as

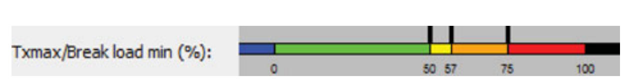

Figure 10. Breaking load limit by colour indicator.

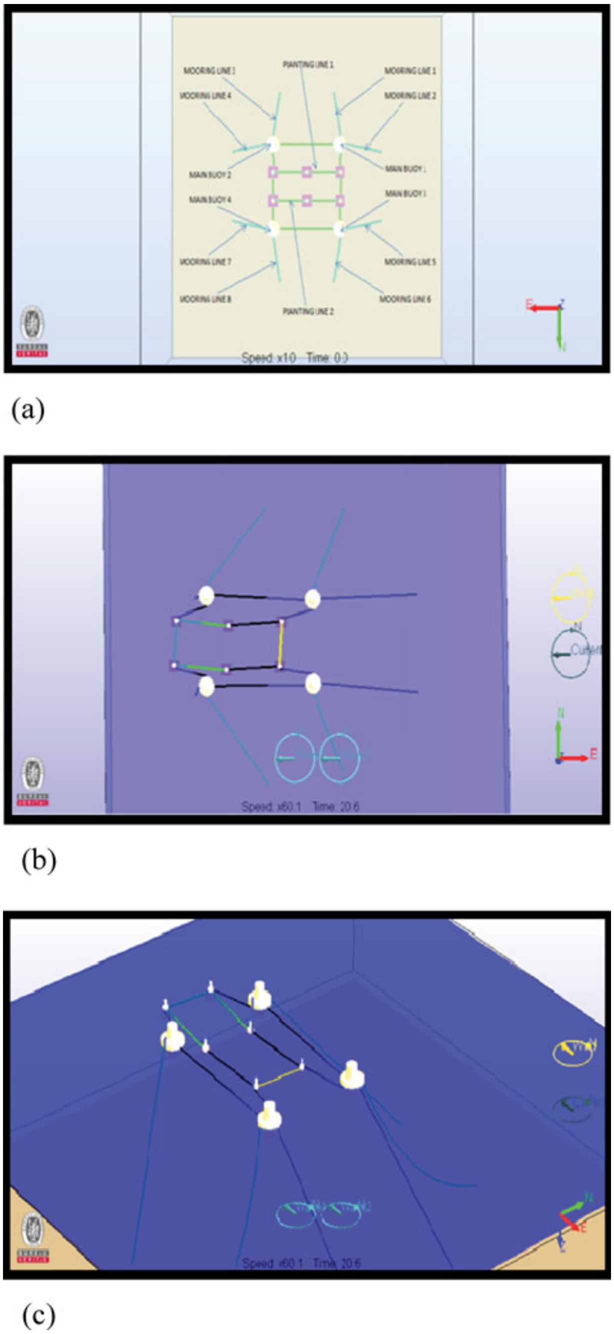

Figure 11. (a) Preliminary model 1 (before). (b) Preliminary model 1 (after). (c) Preliminary model 1 (after).

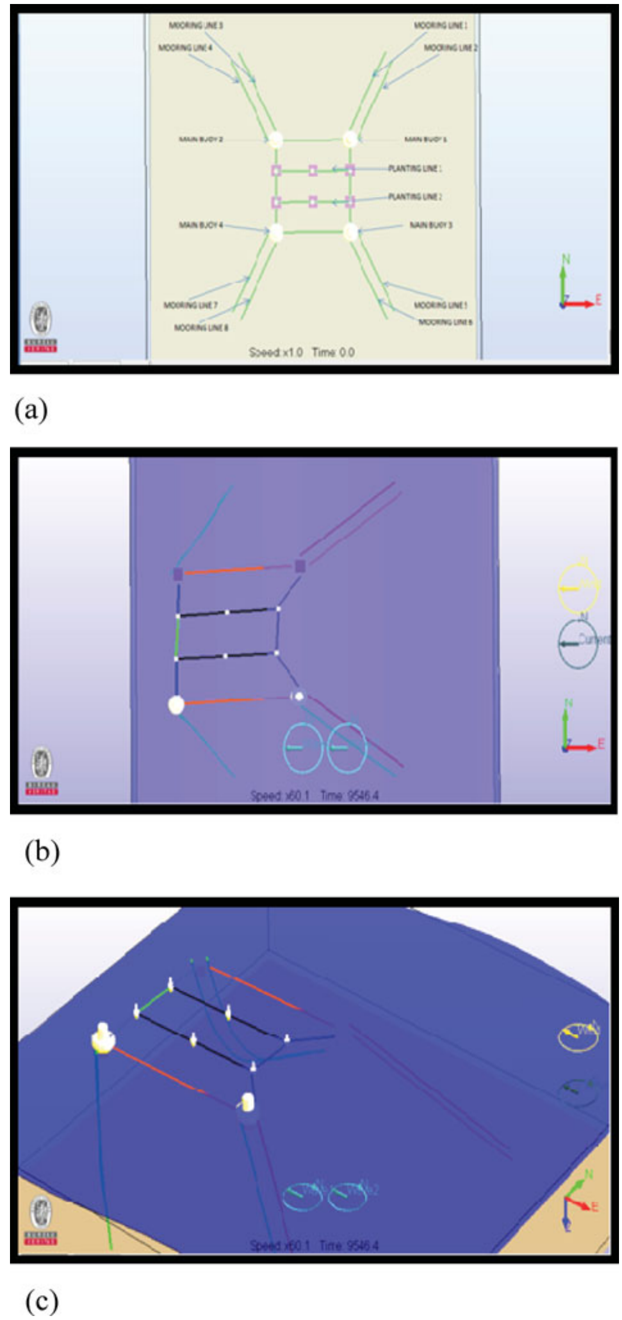

Figure 12. (a) Preliminary model 2 (before). (b) Preliminary model 2 (after). (c) Preliminary model 2 (after).

tension with less than 50% of breaking load and black colour is defined as tension with more than 100% of breaking load.

As shown in Figure 11, the borderlines 1 and 2 are in black colour. Both of the planting line 1 and planting line 2 are also in black colour. This shows that those lines in model 1 are broken due to exceeding 100% of breaking load limit. The mooring lines in each buoy are maintained and not broken although having some tension forces along them. Based on Figure 12, the mooring lines in model 2 are in stable condition and the borderlines exert a high tension. However, both of the planting line 1 and planting line 2 are also in black colour. It is observed in Figure 13 that model 3 is in stable condition and there is no line in black colour. The mooring lines are in stable position. The planting lines are in green colour which means tension exerted on planting line is below 50% of line breaking load.

Simulation of selected model with different depths

As discussed in the previous sections, the seaweed platform model 3 is more stable than the other two models. Thus, the model 3 is tested at the water depth of 100 m. This test is done in order to assess the reliability and toughness of the model at much deeper sea depth. The results from the simulation include buoy elevation movement, mooring line tension at anchor and fairlead as well as tension on planting lines.

Figure 14 shows the animation results of model 3 under the sea depth of 100m after the time domain simulation. As shown

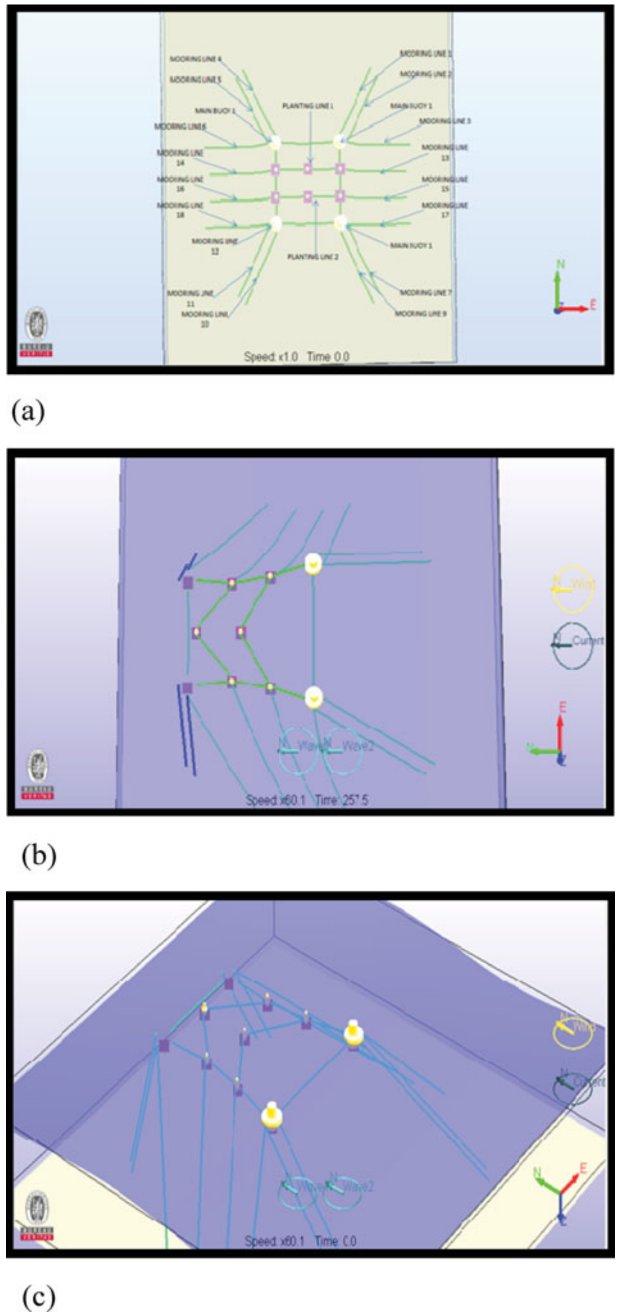

Figure 13. (a) Preliminary model 3 (before). (b) Preliminary model 3 (after). (c) Preliminary model 3 (after).

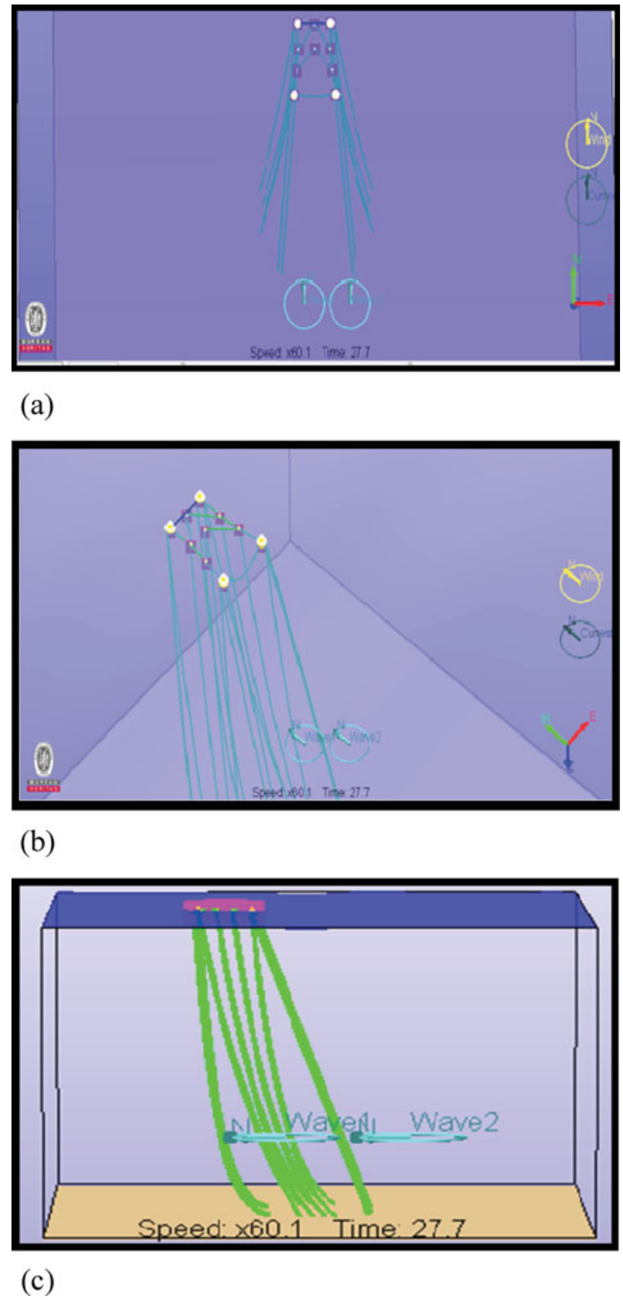

Figure 14. (a) Animation result (above). (b) Animation result (isometric). (c) Animation result (side).

in the figure that the mooring lines in the model are in stable condition and none of the borderlines and planting lines is dark in colour which implies as a broken line. Figure 15 shows the buoy elevation at the depth of 100 m. The graph illustrates a sinusoidal motion resulted from wave motion in the sea. It also shows that the buoy elevation for wave2 is higher than that for wave1.

Figure 16 shows the mooring line tension of the model at anchor and fairlead positions. From the plotted graph, it is observed that none of the lines at anchor and fairlead has horizontal and axial tension higher than the line breaking load limit. The tension forces at fairlead are higher at mooring lines 7, 8, 10 and 12. Figure 17 shows that the tension forces on planting lines do not exceed the line breaking limit. Thus, the seaweed planting

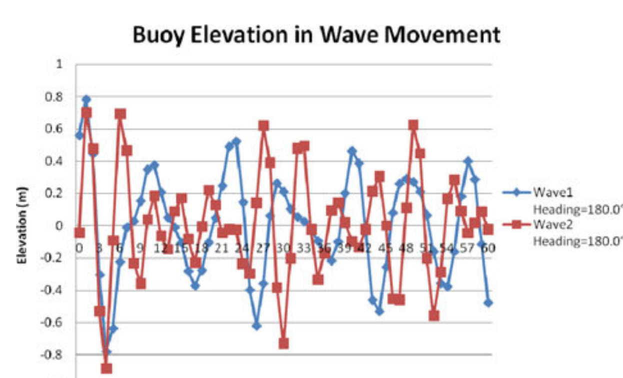

Figure 15. Buoy elevation at the depth of 100 m.

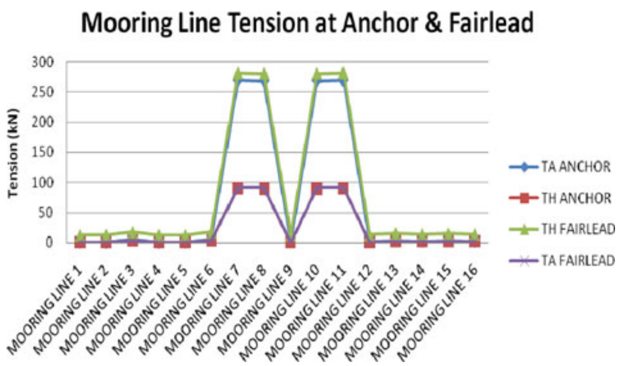

Figure 16. Horizontal and vertical tension at anchor and fairlead.

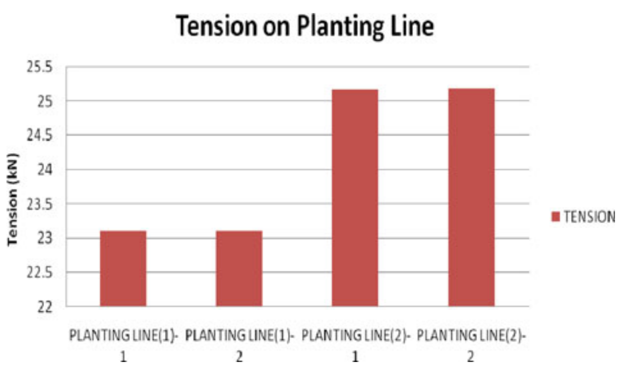

Figure 17. Tension on planting lines.

lines are in safe condition. Overall, the seaweed platform model 3 is suitable for deeper sea depth based on the results obtained from time domain simulation.

Conclusions

This paper presents simulation of offshore aquaculture system for seaweed oceanic farming with mooring assessment using Ariane 7 software. Three types of offshore models with different mooring arrangements are simulated under environmental loads including wave, wind and current. Seaweed platform model 3 is the best design with the most stable mooring arrangement and the least tension acting on each line of the model. The analysis includes tension estimation at the mooring lines, planting lines and other lines in the model and comparison with the line breaking load limit. The platform model 3 is then tested at the water depth of 100m and the results show that it is suitable for deeper sea depth. The simulation is done before the actual platform is built in order to obtain a comprehensive and reliable seaweed mooring platform with the aid of mooring simulation software and model tests.

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No potential conflict of interest was reported by the authors.

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