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〈Original Article〉

Estimation of tuna longline hook depth for improved performance in Fiji

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In pelagic longline, deploying the gear such that the depth of the hook is the same as that of the target fish is important to improve the fishing performance and selectivity. In this study, the depth of the tuna longline hook was estimated using the mass-spring model, catenary curve method, and secretariat of the pacific commission Pythagorean method in order to improve the performance of the longline gear in Fiji. The former two methods were estimated to be relatively accurate, and the latter showed a large error. Further, the mass-spring model accounted for the influence of tidal current in the ocean, which was found to be appropriate for use in field trials.

Keywords : Longline gear, Hook depth, Numerical methods, Mass-spring model, Tuna

Introduction

Fiji is located within the Western Central Pacific fishery region, which represents a critical store of "natural capital" for economic growth in Fiji and other small developing states in the pacific island (Ravitu, 2014). The Fiji Economic Exclusive Zone provides good catches of albacore and other offshore pelagic species; the predominant fishing method in this zone is long lining (Amoe, 2002). The fisheries sector offers employment for numerous people; fish provide an endless source of nutrition and sustenance to the local people, and fisheries are considered important for both their recreational and traditional aspects (Gillet, 2011). The tuna longline fishing industry is very important to the Fiji Government since it was established by the Ministry of Fisheries in 1977. The use of longline is encouraged by fishery management authorities for its conservation aspects. This method involves less fuel consumption, avoids damage to the fishing grounds, allows the capture of good-quality fish and reduces the discards of undersized fish and non-target species (Lokkeborg and Bjordal, 1992).

The Food and Agriculture Organization (FAO) offshore tuna catch data confirm that Fiji is unable to consistently harvest maximum catches of targeted offshore tuna fish species. The catch per unit effort of tuna species registered in 2001 remained fluctuating until 2011. The catch rate of offshore tuna species in Fiji has remained steady for the past 5 years, according to the FAO offshore fishery catch data (WCPFC, 2012). The Fiji Government needs to prioritize the improvement of the fishing efficiency of tuna longline gear to maintain consistent harvest of tuna fish species.

The reach depth of a hook in pelagic longline fishing

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is very important for fishing performance. The hook depth can be determined by analyzing the shape of the fishing gear. Although the longline fishing gear has long been used, its shape has not yet been accurately determined. Most of the previous interpretations are considered to be catenary curves (Irvine, 1981; Kim, 1999). Recently, a comparison between flume tank experiment and static methods and a dynamic method involving the use of the mass-spring model was conducted (Lee et al., 2005b; Song et al., 2015).

This study aimed to improve the performance of the longline fishing gear used in Fiji by estimating the hook depth of this gear by using the mass-spring model (MSM), catenary curve method (CCM), and secretariat of the pacific commission (SPC) Pythagorean method and to determine the most accurate method among them.

Methods and Materials

Mass-spring model (MSM, Lee et al., 2005b)

For the modeling of longline gear, we described the mathematical model by dividing the line element at regular intervals, placing the mass point at the center of the divided elements, and connecting these mass points to the elastic lines (Fig. 1). The detailed description of the mathematical model is described in a previous article (Lee et al., 2005b); therefore, we briefly describe the mathematical model below.

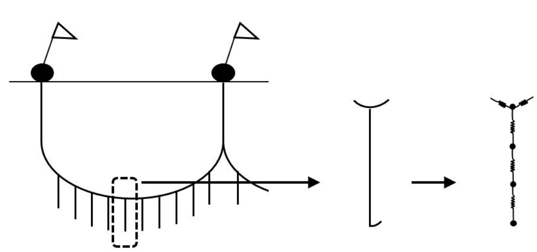

Fig. 1. Longline gear as a coordinated system by using the mass-spring model.

The equation of motion, according to Lee et al. (2005a), can be described as follows:

$$(m + m_a)\ddot{\mathbf{q}} = \sum \mathbf{f} \tag{1}$$

Where m is the mass of the mass point, m_a is the added mass, $\ddot{\mathbf{q}}$ is the acceleration vector, and $\mathbf{f}$ is the sum of the forces acting on the mass point. The added mass, m_a of the structure is given as follows:

$$m_a = \rho_w \mathrm{V}_N \tag{2}$$

Where ρ_w is the density of the seawater, and V_N is the volume of the element.

Two types of forces can be considered to influence the gear shape: internal force and external force. The internal force can be described as follows:

$$\mathbf{f}_{\text{int}} = -k\mathbf{n}(|\mathbf{r}| - l^0) \tag{3}$$

Where k is the stiffness of the line, $\mathbf{n}$ is the unit vector along the line of the spring, $\mathbf{r}$ is the positive vector between the neighboring mass points, and l^0 is the original spring length. The unit vector $\mathbf{n}$ might be obtained by dividing the vector $\mathbf{r}$ by its magnitude. The force $\mathbf{f}_{\text{int}}$ is proportional to the displacement of the spring measured from the original length, and $\mathbf{n}(|\mathbf{r}| - l^0)$ is the displacement in three-dimensional space.

External forces, which represent the interaction of mass points with the environment, include drag, lift, buoyancy, and sinking forces. The drag that acts on the mass points is a decisive factor in shaping fishing gear when it is launched into the water, or when it is set. The drag can be described as follows:

$$\mathbf{F}_D = -\frac{1}{2} C_D \rho S V^2 \mathbf{n}_v \tag{4}$$

Where C_D is the coefficient of the drag; ρ is the density of the fluid; S is the projected area of the structure; and V is the magnitude of the resultant velocity vector $\mathbf{V}$,which includes the velocity of the mass point and the current velocity vector. $\mathbf{n}_v$ is the unit vector for drag and acts in the inverse direction of the

Table 1. Specification for the simulation of the longline fishing gear

Item	Specification
Mainline	
Material	Nylon monofilament
Diameter (mm)	3.5
Length (m)	11,000 / 16,000 / 21,000 / 26,000 / 31,000
Density (g/cm^3)	1.14
Branch line	
Material	Nylon monofilament
Diameter (mm)	1.5
Length (m)	20
Number (ea)	10 / 15 / 20 / 25 / 30
Density (g/cm^3)	1.14
Buoy line	
Material	Tarred red polyester
Diameter (mm)	6.4
Length (m)	30
Number (ea)	25
Density (g/cm^3)	1.4
Radio beacon buoy line	
Material	Tarred red polyester
Diameter (mm)	6.4
Length (m)	50
Number (ea)	2
Density (g/cm^3)	1.4
Buoy	
Material	Hard plastic
Diameter (mm)	360
Weight (kg/air)	3.9
Buoyancy (kgf)	30
Number (ea)	25
Radio Beacon	
Material	Hard plastic
Diameter (mm)	410
Weight (kg/air)	20.5
Buoyancy (kgf)	157
Number (ea)	2
Hook	
Material	Stainless steel circular hook
Diameter (mm)	4.1
Weight (kg/air)	0.0154
Number (ea)	200

resultant velocity vector. The angle of attack α between the velocity vector $\mathbf{V}$ and the position vector $\mathbf{r}$ needs to be determined in order to decide the coefficient of drag. The attack angle is determined as follows:

$$\alpha = \cos^{-1}\left[\frac{\mathbf{V}\cdot\mathbf{r}}{|\mathbf{V}||\mathbf{r}|}\right] \tag{5}$$

The sheer force is defined as

$$\mathbf{F}_L = \frac{1}{2}C_L\rho S V^2 \mathbf{n}_L \tag{6}$$

Where C_L is the coefficient of the sheer force, determined by the angle α; ρ, S, and V are as previously defined. The most important factor in the equation of lift force is the direction of operation $\mathbf{n}_L$ because force works at 90° to the drag. The direction of operation of lift forces for each element is obtained by the vector product $\mathbf{V}\times(\mathbf{V}\times\mathbf{r})$, and the unit vector $\mathbf{n}_L$ of this direction is expressed as follows:

$$\mathbf{n}_L = \frac{\mathbf{V}\times(\mathbf{V}\times\mathbf{r})}{|\mathbf{V}\times(\mathbf{V}\times\mathbf{r})|} \tag{7}$$

Where $|\mathbf{V}\times(\mathbf{V}\times\mathbf{r})|$ is the magnitude of this vector. The buoyancy and sinking force of the structures $\mathbf{F}_B$ can be described as follows:

$$\mathbf{F}_B = (\rho_i - \rho_w)\,\mathrm{V}_N\,\mathbf{g} \tag{8}$$

Where ρ_i is the density of the material, ρ_w is the density of the seawater, V_N is the volume of the elements, and $\mathbf{g}$ is the acceleration due to gravity.

The behavior of the longline gear was determined by integrating the mathematical model described above. The structure of the calculated gears was changed from 10 to 30 hooks per basket, and the shortening ratio was changed to 0.7, 0.8, and 0.9. Table 1 shows the physical properties of the calculated longline gears. The differential equation can be solved using fourth-order Runge-Kutta method by using 0.0002s step sizes.

The catenary curve method (CCM, Irvine, 1981)

The CCM is a uniform curve, an inextensible line that hangs between two fixed points that are at the same level. The elements of the line are assumed to be perfectly flexible, and the cable is also as assumed to sustain tension force (Irvine, 1981).

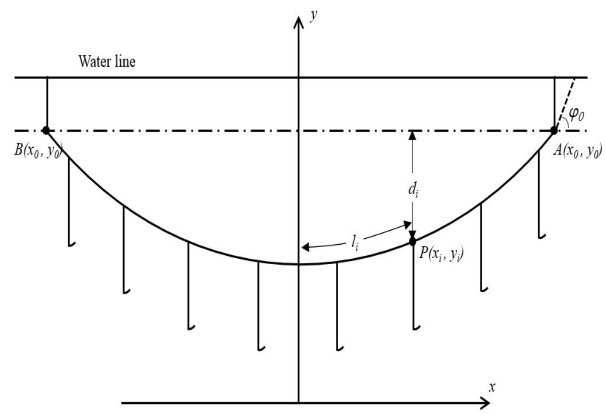

Fig. 2. Longline gear displacement analysis by using the catenary curve method. (Source: Kim, 1999)

The equation to determine the mainline depths, according to Kim (1999), is described as follows:

$$d_i = l_0\left\{\mathrm{cosec}\,\varphi_0 - \sqrt{\left(\frac{l_i}{l_0}\right)^2 + \cot^2\varphi_0}\right\} \tag{9}$$

Where d_i is the distance from the bottom of the buoy line to the deepest point of the mainline, l_0 is half the length of the mainline at full stretch, l_i is the initial point, and $\mathrm{cosec}\,\varphi_0$ and $\cot^2\varphi_0$ are shortening ratio constants. The shortening ratio is described as follows:

$$K = \frac{x_0}{l_0} \tag{10}$$

Where x_0 is the horizontal distance of the buoy from the center of the longline basket at full stretch. According to Hamuro and Ishii (1958), the shortening ratio is also estimated as the ratio of vessel speed to the mainline setters releasing the speed.

Secretariat of the pacific community analysis method (SPC, Beverly et al., 2003)

According to the Pythagorean theorem, the square of the hypotenuse of a right-angle triangle is equal to the sum of the square of the two sides (Beverly et al., 2003). Fishing gear scientists at the SPC used this theorem principal to calculate the mainline depth, A, by using actual fishing gear data recorded by the domestic longline vessels in Fiji and other pacific island countries.

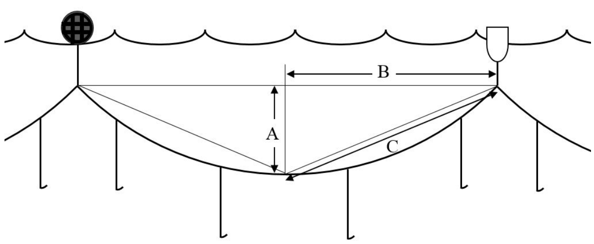

Fig. 3. Application of the Pythagorean theorem analysis for longline fishing gears.
(Source: Beverly et al., 2003)

The Pythagorean theorem equations, according to Beverly et al. (2003), are described below.

$$A^2 + B^2 = C^2 \tag{11}$$

Where A is the mainline depth (this length represents the distant between the lowest points of the buoy line to the deepest point of the mainline, at full stretch), B is half the distance the boat travels between two buoys, and C is half the length of the line between two buoys.

$$C = \frac{L}{2} \tag{12}$$

Where L is the main line length between 2 buoys.

$$B = S \times t \tag{13}$$

Where S is the vessel speed (m/min), and t is the time (min) required for the boat to travel between 2 buoys.

$$A = \sqrt{(C^2 - B^2)} \tag{14}$$

Therefore, the longline hook depth is described as follows:

$$\text{Hook depth} = A + FL + BL \tag{15}$$

Where A is the mainline depth, FL is buoy line length, and BL is the branch line length at full stretch.

The lengths of the float line and branch line needs to be added to the depth of the mainline to yield the hook depth of the longline gears. The mainline depths were determined and calculated using the Pythagorean theorem analysis equation. The proposed specification of the longline was as follows: 50 m, the distance between the branch lines; 30 m, buoy line length; 20 m, branch line length; and 7 knots, vessel speed; the ocean current speed was not considered for the analysis.

Table 2. Theoretical longline mainline depths based on different shortening ratios and basket sizes, proposed by the SPC method

Basket size (No. of hooks)	Mainline depths (m)		
	Shortening ratio 0.7	Shortening ratio 0.8	Shortening ratio 0.9
10	194	163	119
15	288	238	175
20	375	313	231
25	463	388	288
30	556	463	338

(Source: Beverly et al., 2003)

Results and discussion

Longline gear shape analysis performed using MSM

The shape of the longline gear modeled using the MSM was simulated according to the number of hooks and shortening ratio per basket. The gear shape when the number of hooks of 1 basket was 10, 20, and 30 is shown in Figure. 4. The depth of the hook increased with an increase in the number of hooks. The shape of the gear at shortening ratios of 0.7, 0.8, and 0.9 when the number of hooks of 1 basket was set to 10 is shown in Figure. 5. The depth of reach of the hook varied remarkably according to the shortening ratio; the depth of the hook increased with a reduction in the shortening. The findings of the above analysis suggest that the depth of a hook can be controlled by the number of hooks and shortening ratio in 1 basket, as well as by the length of the float line.

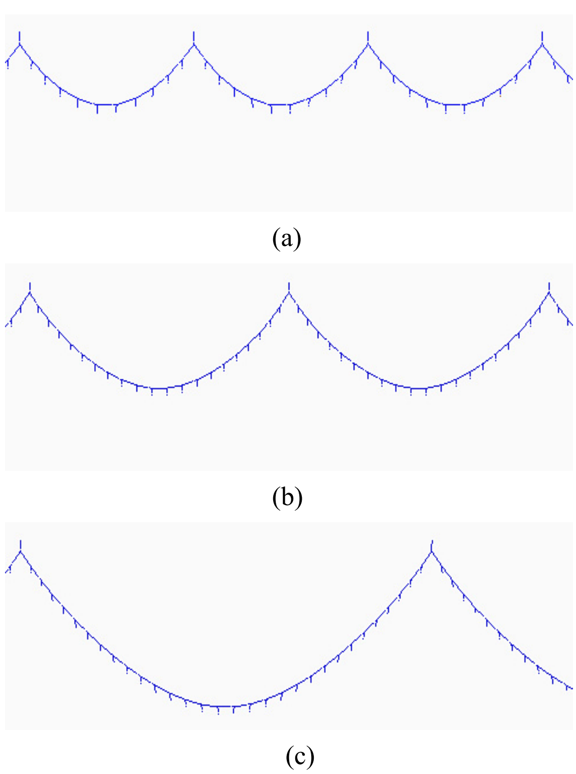

Fig. 4. The shape of the gear according to number of hooks at the shortening ratios of 0.8. (Number of hooks: (a) 10, (b) 20, and (c) 30)

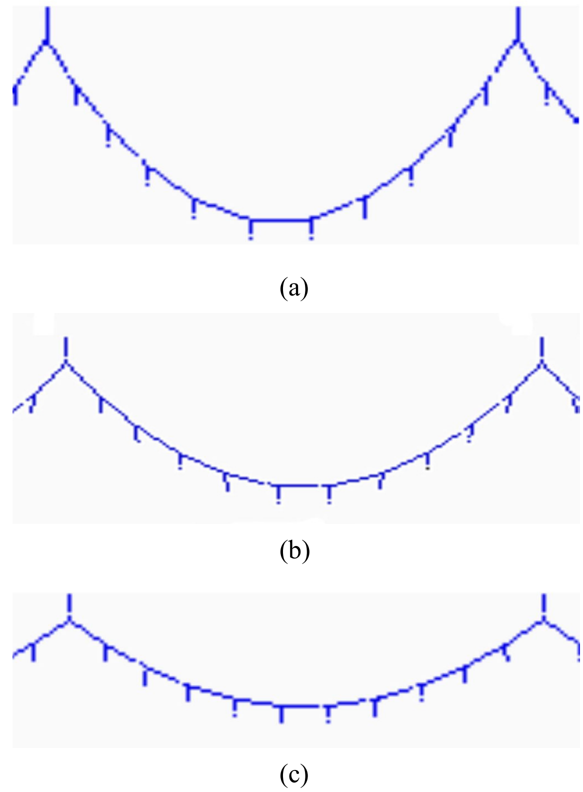

Fig. 5. The shape of the gear according to shortening ratio when the number of hooks is 10. (Shortening ratio of (a) 0.7, (b) 0.8, and (c) 0.9)

Comparison of hook depth according to the computation methods

The hook depth data shown in Table 3 were calculated by adding the float line length and branch line with the mainline depth for the MSM, CCM, and SPC method. The longline hook depths (Table 3) shows the total hook depth of the longline fishing gears when the ocean currents are not considered in the calculations or the analysis.

The hook depth data shown in Table 3 has been represented in Figure 6 for the MSM, CCM, and SPC method at the respective shortening ratios and basket sizes. The hook depths represent the depth of the longline fishing gears when the ocean current is at an equilibrium state.

Table 3. Comparative analysis of the MSM, CCM and SPC method for obtaining longline gear hook depths data

Basket size (No. of hooks)	Hook depths (m)								
	Shortening ratio 0.7			Shortening ratio 0.8			Shortening ratio 0.9		
	SPC	MSM	CCM (0.702)	SPC	MSM	CCM (0.799)	SPC	MSM	CCM (0.909)
10	244	227	226	213	197	196	169	156	159
15	338	314	306	288	268	262	225	204	194
20	425	398	386	363	336	328	281	251	239
25	513	487	466	438	408	395	338	303	284
30	606	520	546	513	485	461	388	354	329

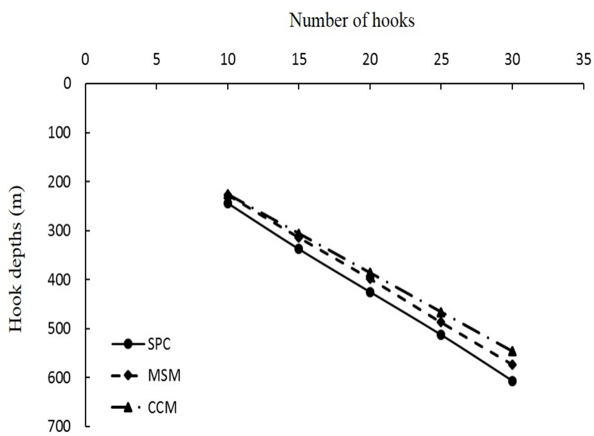

Fig. 6. Hook depths data obtained using the MSM, CCM, and SPC methods at 0.7 shortening ratio.

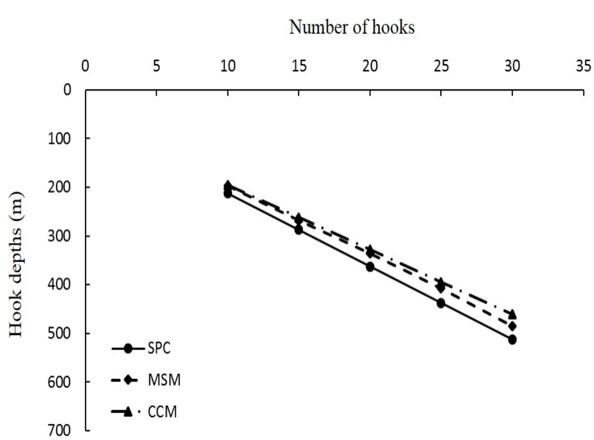

Fig. 7. Hook depths data obtained using the MSM, CCM, and SPC methods at 0.8 shortening ratio.

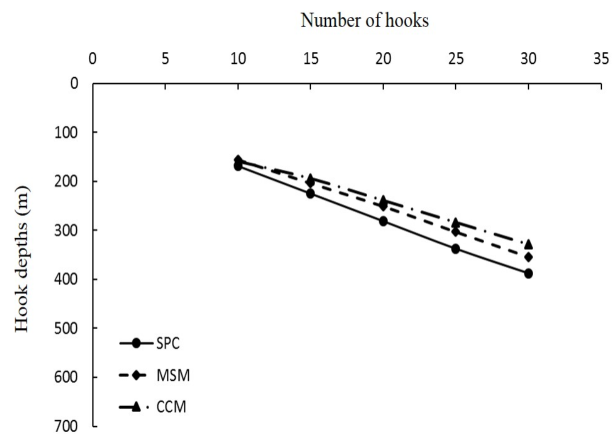

Fig. 8. Hook depths data obtained using the MSM, CCM, and SPC methods at 0.9 shortening ratio.

The hook depth was the highest with SPC method, followed by that with the MSM and CCM (Fig. 6). This tendency is also evident in Fig. 7 and 8. Moreover, the water depth variation according to the calculation method increased as the number of hooks per basket increased. In Fiji, the water depth of a hook is predicted using the SPC method. The results of our analysis suggest that this method is erroneous and requires improvement.

The SPC method yields a considerably greater hook depth than that calculated by the MSM and CCM, as shown in Fig. 6, 7, and 8. This is an inevitable problem because of the principle of water depth in the SPC method. Since the length of C is half that of the main line in Figure. 3, water depth is exaggerated as shown in Figure. 9. Therefore, the hook depth needs to be reduced by 20% when using the SPC method (Viliame, 2017). However, if this is reflected in the calculation the water depth becomes too shallow.

In this study, we compared and analyzed the hook depth data obtained from this study and those reported previously to determine the method that can make an accurate prediction. The data used in the comparison are those of Song et al. (2015). According to their data, the depth of hook at the center when the number of hooks per basket is 10 was found to be 178.8 m, and the predictions by the three calculation methods used in this study are 197 m as per the MSM, 196 m as per the CCM, and 225 m as per the SPC model. The difference between the measured values in the field experiment and those obtained in this computation are relatively large and show the largest errors in the SPC method. This is because the tidal current acts on the experimental site, leading to variations in water depth. The MSM and CCM are likely valid considering that the depth of the water decreases by 10% when the tidal current in the ocean 0.1 m/s (Lee et al., 2005b). However, the CCM has a disadvantage in that it provides an equilibrium shape; thus, reflecting the physical properties of the longline gear is difficult, and the influence of the current cannot be considered. Therefore, even though the calculation process is somewhat complicated, the prediction obtained using the MSM is desirable.

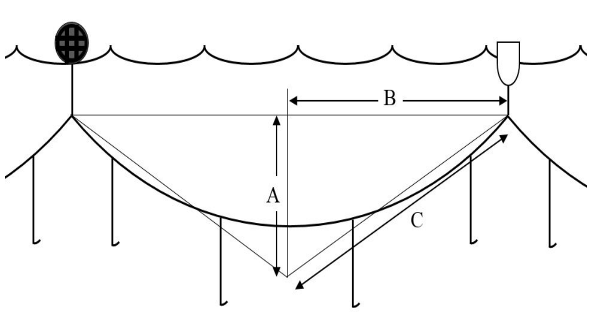

Fig. 9. Application of the exaggerated water depth for longline fishing gears.

Deploying a hook at the depth of the target fish species is also important for improving the fishing performance; further, it is advantageous in terms of resource conservation because capturing only the target fish species selectively is possible. In this study, the accuracy of the hook depth of pelagic longline gear was estimated using three methods. The analysis showed that the MSM is promising for its accuracy and scalability. Traditionally, catenary curves provide relatively accurate predictions in equilibrium without considering the tidal current; however, they are less accurate in the real ocean with tidal current. The SPC method used in Fiji and other Pacific coast countries inevitably predicts deeper hook depth owing to the calculation principle, and the tidal current cannot be considered as that in the catenary curve.

From the perspective of rigging of longline gears, the shape of gears might change when the design parameters of the gear, such as the main line and branch line material and thickness, change. Changes in these design requirements should be considered while estimating the hook depth, but they are difficult to be reflected in the catenary model and the SPC method. However, the MSM considers the changes in the parameters related to all gear designs in the calculations.

However, MSM is difficult to use in the field by fishermen because it requires complex and long calculation process. Therefore, in the future, research on simple computational models based on scientific calculations and easy to use by field fishermen should continue.

Conclusion

In this study, three types of hook water depth estimation methods were compared and analyzed. The analysis compared the field data with the estimated values, and the mass-spring method and catenary curve method were found to provide relatively good estimates. However, since the catenary curve method does not consider the influence of the tidal current, the mass-spring method was considered to be more suitable in terms of accuracy and scalability. The SPC method, which is traditionally used in Fiji, miscalculates the depth of the hook and the influence of the tidal current cannot be considered. Further, judging from the rigging and design aspects of the gear, the mass-spring method is the only method that can be used to reflect the changes in the design parameters of the longline gear.

However, since the MSM requires a complicated numerical calculation process, it is preferable to make a table of the pre-calculated data so that the fishermen can easily use it in the field. In the future, there is a need for a simplified model derivation where the shortening ratio and the hook number per 1 baskets are given and the depth of the hook is calculated.

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