4 Anchored FAD technical considerations

The basic design of an anchored FAD consists of an upper floatation (buoyancy, rope and aggregators), the main line (main line rope, connections and supplementary buoyancy) and the anchor (chain and anchor/s). In this part of the manual we have separated these sections to identify the technical considerations of the components used in each section, highlighting some of the common errors made during the construction and deployment of FADs.

4.1 FAD Upper floatation technical considerations

The upper floatation of an anchored FAD provides the buoyancy to keep the main line ropes from tangling and to keep the FAD system vertical. This floatation can be on the sea surface (e.g. bamboo, Indo-Pacific and spar buoy type FADs) or below the surface (e.g. lagoon and sub-surface FADs). Sabotage or vandalism of the upper floatation has been identified as one of the major factors resulting in premature FAD losses across the Pacific region (Sokimi and Albert 2016). Surface floatation can also be a navigational issue, resulting in boat entanglement and premature FAD losses. The evolution of the sub-surface FAD has largely come about in response to these issues.

Upper floatation used for both surface and sub-surface FADs are designed to ensure that: a) minimal strain is placed on the main line because drag is reduced; b) floatation is retained, even in situations where currents drag the upper floatation section to deep depths; and c) the design is suitable to the characteristics of the site, i.e. considering boat traffic and risks of vandalism.

4.1.1 Buoyancy type

The buoyancy used for FADs may be either locally obtained materials (bamboo/balsa wood) or synthetically produced products (foam or hard plastic floats, e.g. ABS floats). Floats are the most common buoyancy used for anchored FADs, apart from low-cost designs, where bamboo or other locally derived materials are used.

As a general guide, the buoyancy of the upper floatation section needs to increase as you move further offshore, as wave and currents are stronger and the deployment depth (and strain on the mooring line) increases. This is exemplified by the Indo-Pacific FAD, which uses 15 ABS floats with 14 purse-seine buffer floats when deployed offshore and six ABS floats with five purse-seine buffer floats when deployed nearshore.

Table 3 highlights the optimal buoyancy type based on some key parameters.

Table 3. Optimal buoyancy type based on some key parameters (🟩 = optimal, 🟦 = sub-optimal, 🟧 = ok, but not recommended, 🟥 = not appropriate).

	Bamboo	Surface floats	Sub-surface floats	Spar type buoys
Strong current or rough seas	🟥	🟩	🟩	🟩
High boat traffic	🟧	🟧	🟩	🟩
High vandalism	🟩	🟥	🟩	🟩
Low cost	🟩	🟧	🟩	🟥
Commonly available in PICTs	🟩	🟧	🟧	🟧

When choosing floats it is necessary to know their floatation capacity (or buoyancy) and their working depth. The working depth of a float is the ability for the float to maintain integrity due to the increased pressure with increasing depth. It is recommended to use a float with a working depth at least double that of the actual depth of the float, as there will be times when the float is pulled into deeper water, for example during deployment and during periods of high current. Table 4 provides the floatation capacity (buoyancy) and working depth of some common floats used for FADs in the region.

Table 4. Common floats used, their floatation capacity (buoyancy) and working depth.

	Dimensions (mm)		Buoyancy	Working depth	Notes
Float	Diameter	Length			
Purse-seine (oval, Ethylene Vinyl Acerate (EVA) float)	220	250	7 kg	surface	Crushes when constantly submerged
30G-2 (oval ABS float)	290	437	20 kg	300 m	Found to implode when constantly plunged to deep depths over long periods. Sharp centre hole edge can cut float rope
10B (round ABS float)	290		10 kg	300 m	Replaced 30G-2 in French Polynesia
12B (round, ABS float)	360		20 kg	300 m	A larger, more buoyant alternative to 10B
Aquafloat-800 (cone, rotationally-moulded foam filled with closed-cell polyurethane)	800	1,260	100 kg	surface	

4.1.2 Surface markers

Surface marker floats, or buoys fitted with flags, provide a navigational aid for fishers to locate nearshore FADs (surface and subsurface). For offshore FADs, the use of special marker buoys, reflectors and strobe lights are required for maritime navigation and to be compliant with International Maritime Organization regulations. In some countries this may include the use of IALA approved buoys, such as a Special Mark buoy.

A common flagpole design used for nearshore FADs (Figure 12) consists of a 2 m length of PVC pipe (minimum 24 mm), inserted through the centre hole of an ABS float (290 mm diameter and 20 kg buoyancy) and held in place with at least four rounds of rope (8 mm), clove-hitched at the top and bottom of the float. A piece of re-bar (5 kg) is inserted into the bottom of the PVC pipe and whipped to the pipe to give weight to the flagpole and ensure it stands vertically in the water column. Multistrand nylon rope (16 mm) is whipped to the PVC pipe to connect the flagpole to the main float line. Alternative poles can also be used (bamboo, fibreglass or timber) as long as the diameter is less than the internal diameter of the float centre hole.

4.1.3 End point connections

The end point of the main float line (at the end of the floats) is an important connection point to enable the attachment of a flag or surface marker and is the final point that stops the floats from coming off. A common end point connection is the eye loop (Figure 13). The loop acts a back-up float stopper and provides an easy connection point for the attachment of flags and aggregators. Ensure that the main float line is spliced back on itself and whipped well. Take particular care with binding the end connection of the Indo-Pacific and subsurface FAD designs that have a poly pipe sheath encasing the rope (see also Figure 19).

An alternative end point connection (Figure 14) is the detachable loop, used for example in bamboo FAD designs. The main line is spliced directly to the surface float, while an additional line is spliced and whipped to the main line about 1 m below the surface float, with an eye loop at the end. This eye loop provides the point for the connection and detachment of the bamboo raft to easily enable its removal for replacement or maintenance, or prior to the onset of the cyclone season.

Surface marker floats (e.g. for sub-surface FADs) with a centre hole can be attached by threading the rope through the float and splicing it back onto itself (Figure 15). This marker float is not intended to last, but provides the location of the FAD, prior to fishers marking the FAD with a GPS or using traditional navigational marks.

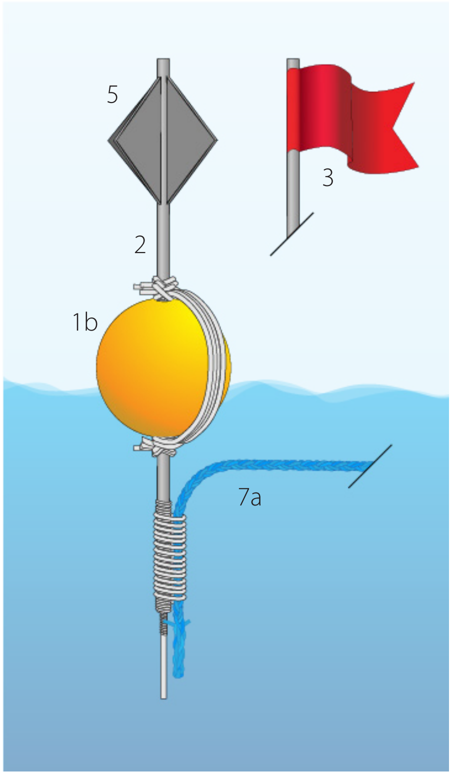

Figure 12. Diagram showing the rope connection to the flagpole.

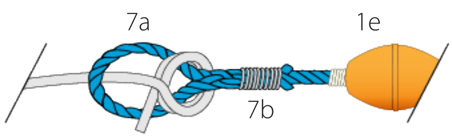

Figure 13. Diagram showing the end loop connection on the upper floatation.

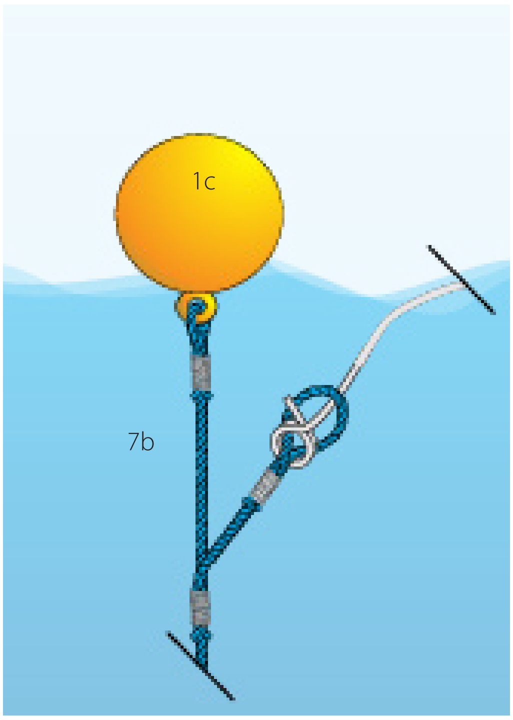

Figure 14. Diagram showing the detachable loop on the upper floatation for the bamboo FAD.

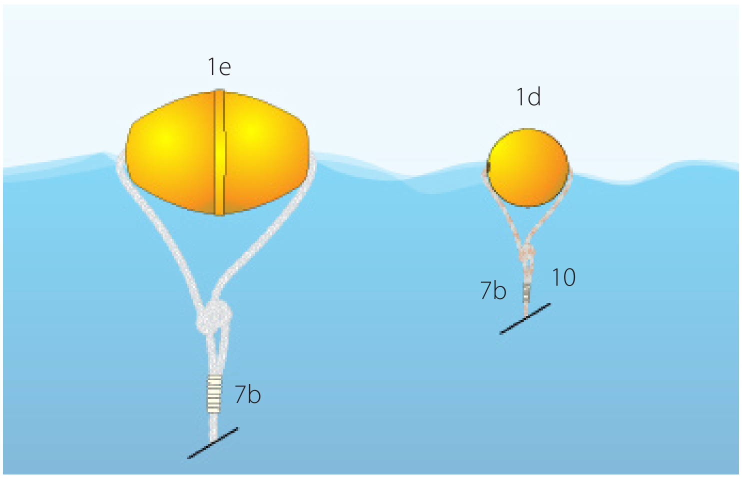

Figure 15. Diagram showing the end connection to a surface float with a centre hole.

4.1.4 Float buffers

Due to the intense pressure on the upper floatation section, buffers between floats are required to stop the floats from rubbing against each other. This constant friction can weaken the main float rope and result in the loss of the FAD.

Buffers can be achieved through several techniques:

1. whipping (Figure 16) between the buoys with polypropylene rope (16 mm) using six turns around the main line (e.g. sub-surface FAD);
2. twisting (Figure 17) multistrand rope (12 mm) through the main line close to each float to block the float (e.g. French Polynesia FAD); and
3. using purse-seine buffer floats (Figure 18) between the larger 30G-2 oval floats for surface FAD designs (e.g. Indo-Pacific and lizard FAD designs).

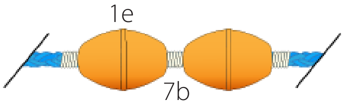

Figure 16. Diagram showing the whipping between buoys, e.g. sub-surface FAD.

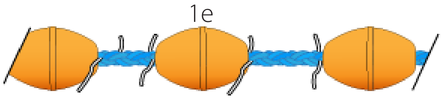

Figure 17. Diagram showing the twisting rope between buoys to block buoys from moving.

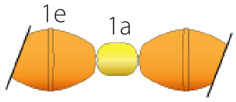

Figure 18. Diagram showing the use of a purse-seine float (yellow) as a buffer between 30G-2 (orange) floats.

In the Indo-Pacific, lizard and sub-surface FAD designs, the main float line is also encased in a plastic tube sheath (20 mm diameter) in the float section. This is especially important when using 30G-2 floats, which have a jagged join line near the centre hole. Extreme care needs to be taken at the two tube end points to ensure that the edge of the tubing is rounded – if the edge of the tubing is sharp, it will cut the rope at that point.

To ensure the main line is protected at the end of the tubing;

- split the tube slightly at the end to fold the tubing back onto itself (this creates a rounded smooth edge);
- gently push back the tubing and whip the rope underneath (about 20 cm either side of the pipe end point);
- bring the tubing back over the whipping and whip the end part of the tubing (where it is folded back on itself) to hold it in place; and
- repeat for the other end of the plastic tube.

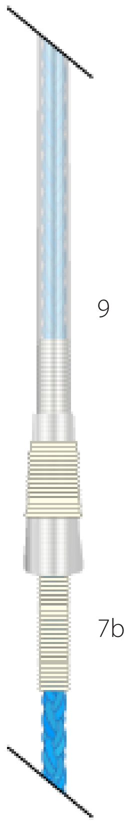

Figure 19. Diagram showing the binding onto the poly pipe sheath.

Image 1 shows a FAD that was poorly constructed. The FAD was in the water for less than one month before washing ashore. While the FAD was lost due to a different connection than the one pictured here, you can see that the whipping around the plastic tubing was not tight or long enough to hold the tubing in place. If other sections of this FAD did not break, eventually the tube would have cut the rope at this point.

Image 1. Plastic tube that has not been constructed appropriately.

4.1.5 Aggregators

It is widely accepted that the attachment of aggregators to the FAD upper floatation system can increase the effectiveness of the FAD for aggregating and retaining fish. A wide variety of materials have been used to rig FADs in the past, including coconut fronds, plastic strapping, fish netting and shade cloth. Plastic strapping and fish netting are no longer recommended, as the strapping contributes to plastic pollution and fish netting has been found to entangle marine life and places undue stress and weight on the system.

Aggregator designs should be streamlined so that they create little resistance on the anchor system. This manual recommends the use of biodegradable aggregators, including coconut fronds, jute, hessian bags (cut into strips), manila, hemp, sisal, bamboo strips or pandanus strips (like those used for weaving mats). The use of materials such as pandanus strips provides an opportunity for all members of the community to participate in the FAD planning and rigging process.

The attachment methods for aggregators have also evolved over the past few decades. In the past, aggregators were attached directly to the main line, but in some situations this resulted in entanglement or friction with the main line, causing weakness in the system. For surface FADs, a secondary aggregator rope line is now recommended (Figure 20, left). This rope runs parallel to the main mooring line and is spliced and whipped to the main line at the top, bottom and at various points along the extent of the rope to prevent the aggregator line twisting and interfering with the main mooring line. For sub-surface FADs that use a plastic tubing buffer between the main rope line and the buoys, the aggregators can be attached directly onto the whipping between the buoys (Figure 20, right).

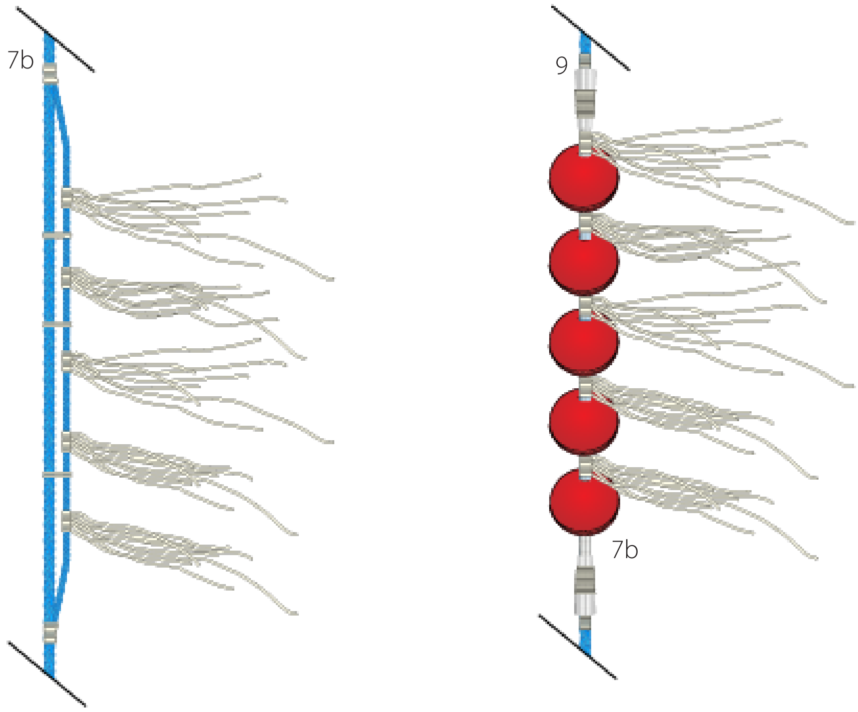

Figure 20. Diagram showing the attachment of aggregators using a secondary rope (left) and to the plastic tubing sheath on a sub-surface FAD (right).

Surface aggregators are also extremely effective. Coconut fronds are one of the most commonly available and effective surface aggregators. The fronds provide protection for small fish and are covered quickly with a film of algae, which provide food, thus creating a small ecosystem around the FAD. The surface aggregator is made up of 5–30 m of coconut fronds, connected to the upper FAD section at the end loop, either end-to-end (Figure 21, bottom diagram) or bunched (Figure 21, top diagram). More coconut fronds can be connected when in series, but in low currents it has been found that the coconut fronds can tangle with the upper floatation. A 5 kg weight (e.g ½ bag of sand) is attached at the end of the coconut fronds to help them sink slightly in the water. The coconut fronds should be replaced regularly, although experience from a number of countries shows that this often does not happen.

A common error amongst FAD practitioners in the region is the use of burdensome aggregators, e.g. large bamboo rafts with extensive amounts of purse-seine net attached underneath. While this type of aggregator is effective to aggregate fish, it substantially shortens the life of the FAD system and will result in premature loss. Bamboo raft aggregators should be used only in areas of low current (e.g. lagoons and bays).

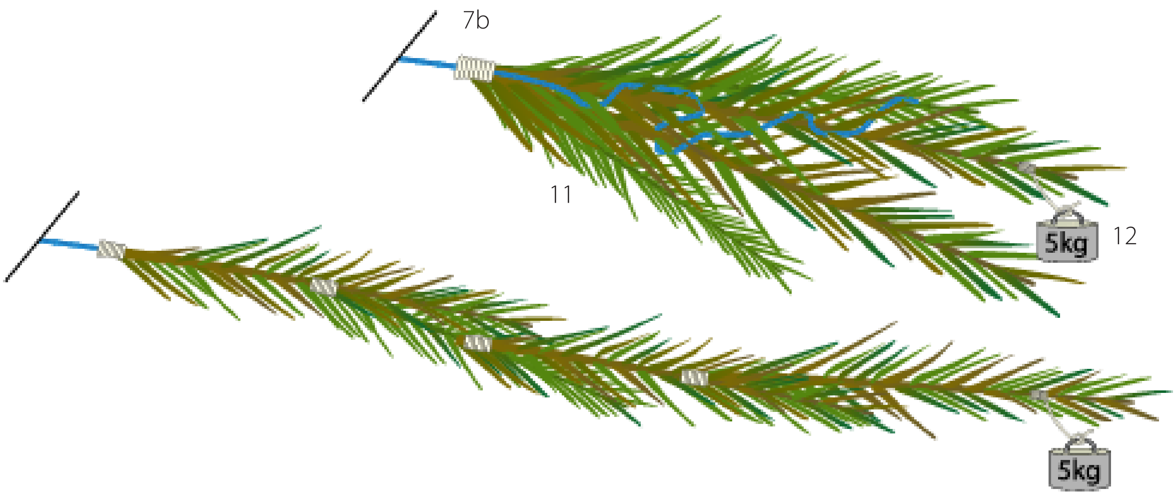

Figure 21. Diagram showing streamlined bamboo aggregators connected end-to-end in series (bottom) and bunched (top).

4.2 FAD main line technical considerations

The main line of an anchored FAD is the link between the upper floatation and the anchor system. It includes the main line rope, connections and supplementary buoyancy. The main lines that are recommended for anchored FADs in this manual have been designed to cope with the forces produced by waves and currents, taking into consideration aspects such as rope entanglement due to boat traffic and/or fishing methods.

Over the past few years, multistrand ropes have become increasingly available in the region and so are now preferred for all FAD construction. Multistrand ropes have a greater holding strength and do not twist, knot or hockle like three-strand ropes. The shift to multistrand rope has reduced the amount of hardware required in the mooring section, which has been identified as a weak point of FAD designs. An increased holding strength has also enabled the use of 16 mm multistrand rope instead of 18 or 20 mm three-strand rope, as recommended in previous manuals (16 mm multistrand rope is also cheaper and often more available in PICTs). The main line rope calculations provided in this manual are based on the use of 16 mm multistrand rope. If 18/20 mm rope is used, follow rope length calculations provided in Chapman et al. 2005.

The catenary curve is an important aspect of surface FAD designs, as it provides the elasticity in the system to cope with tide, currents and wave action. The catenary curve is a theoretical U-shaped curve, created using the combination of sinking (e.g. nylon) and buoyant (e.g. polypropylene) ropes – the catenary curve centres around the point where the two ropes are spliced together. Unfortunately sinking rope is expensive and not readily available in all PICTS. Consequently, low-cost designs (e.g. the lagoon FAD and the bamboo FAD) have been developed with buoyant rope only. Several countries have also modified Indian-ocean type surface FAD designs to use only buoyant rope in the main line (e.g. Vatuika FAD).

This manual provides technical information for calculating main line rope lengths when using a combination of sinking and buoyant rope and for when using only buoyant rope. Sub-surface FADs use only buoyant rope and are considered separately in this section of the manual.

Table 5. Optimal FAD mooring system designs based on different parameters (🟩 = optimal, 🟦 = sub-optimal, 🟧 = ok, but not recommended, 🟥 = not appropriate).

	Buoyant rope without counterweight (surface FAD)	Buoyant rope with counterweight (surface FAD)	Buoyant rope (sub-surface FAD)	Combination sinking and buoyant rope (catenary curve)
Strong current	🟥	🟦	🟦	🟩
Proximity to reef or slope	🟥	🟦	🟩	🟦
High boat traffic	🟥	🟦	🟩	🟦
Rope availability	🟩	🟩	🟩	🟦
Low cost	🟩	🟩	🟦	🟧

4.2.1 Buoyant rope main line: Surface FADs

Buoyant rope is typically used for the main line rope of low-cost surface FADs anchored close to shore (e.g. lagoon and bamboo FADs). The standard calculation for the length of the main line rope is deployment depth plus 25% to allow for scope (see section 4.2.3) and elasticity in the system. Table 6 provides a guide for the lengths of buoyant rope (16 mm polypropylene) required for deployment depths between 50 m and 3,000 m.

Limitations of using only buoyant rope in surface FADs, particularly those located further from shore, are the reduced elasticity in the system (a catenary curve is not created) and the increased potential for boat/fishing line entanglement in the main line near the surface. To avoid these issues, a series of counterweights can be attached to the main line to produce a quasi catenary curve. It is important that the weight and location of the counterweight is appropriate for the deployment depth and type of counterweight used (Table 6) to ensure that the catenary curve created is at a safe depth.

Two common counterweights used are short lengths of cement-filled pipes and lengths of galvanised chain. Cement-filled pipes can be constructed by cementing a piece of rope through a length of poly pipe. Counterweights should be rigged to reduce entanglement with the main line by whipping them alongside the main line, rather than letting them hang from one point (Figure 22).

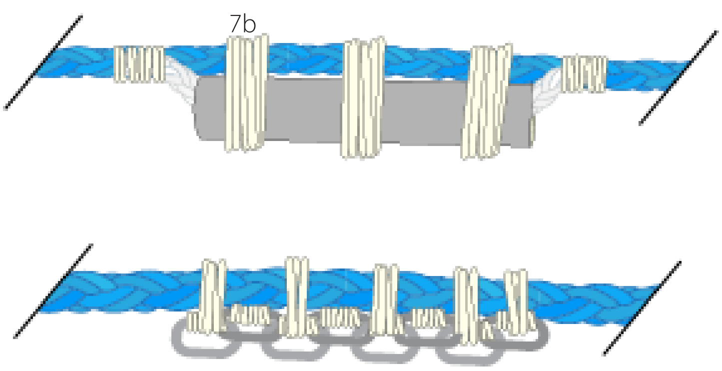

Figure 22. Diagram showing two counterweight options – cement tube (top) and galvanised chain (bottom) – and how they are rigged to the mooring line.

Table 6. Buoyant rope mooring section showing rope length (using 16 mm polypropylene), counterweight required and placement of counterweight.

DEPTH (m)	Length (m) of polypropylene main line rope (16 mm) required	Placement of counterweight (distance [m] from surface)	Underwater counterweight required (kg)	Concrete counterweight (weight in air [kg])	Galvanised chain counterweight (weight in air [kg])
50	65	20	5	9	6
100	125	40	6	10	6
150	190	60	6	11	7
200	250	80	6	11	7
250	315	100	6	12	7
300	375	120	7	12	8
350	440	140	7	13	8
400	500	160	7	13	8
450	565	235	8	15	10
500	625	245	9	15	10
550	690	255	9	16	10
600	750	265	9	16	10
650	815	270	9	16	10
700	875	280	9	16	11
750	940	290	9	17	11
800	1,000	300	9	17	11
850	1,065	310	10	17	11
900	1,125	320	10	17	11
950	1,190	325	10	18	11
1,000	1,250	335	10	18	11
1,100	1,375	355	10	18	12
1,200	1,500	375	11	19	12
1,300	1,625	390	11	19	12
1,400	1,750	410	11	20	13
1,500	1,875	430	11	20	13
1,600	2,000	445	12	21	13
1,700	2,125	465	12	21	14
1,800	2,250	485	12	22	14
1,900	2,375	500	12	22	14
2,000	2,500	520	13	23	15
2,100	2,625	540	13	23	15
2,200	2,750	555	13	24	15
2,300	2,875	575	14	24	16
2,400	3,000	595	14	25	16
2,500	3,125	610	14	25	16
2,600	3,250	630	14	26	16
2,700	3,375	650	15	26	17
2,800	3,500	665	15	26	17
2,900	3,625	685	15	27	17
3,000	3,750	705	15	28	18

4.2.2 Buoyant rope only main line: Sub-surface FADs

Only buoyant rope is used for the main line rope of sub-surface FADs, as the upper floatation section is submerged. The standard calculation for the length of main line rope required for sub-surface FADs needs to take into consideration the deployment depth, the settling location of the top of the buoyancy section (typically 20 to 40 m below the surface), the stretch in the rope (as a result of the positive buoyancy pressure on the mooring system), as well as other components included within the overall deployment depth, such as anchor height and chain length.

Figure 23 shows the components required for the calculation of subsurface main line length. The calculation is shown below.

Main line rope length (MRL) = deployment depth (d) – (settling depth of top float (a) + height of anchor block (c) + length of anchor chain above anchor (b)) + (stretch of main rope x length of the rope (r)

$$MRL = d - (a + c + b) + (stretch\% \times r)$$

Different rope types and diameter have different stretch. Nylon rope is not recommended for sub-surface FADs as it has sinking properties that will require more floats to hold up the system and it has greater stretch than polypropylene rope at 15% to 25% during usage. Polypropylene rope has 5% to 10% stretch during usage. Stretch properties for the rope used for the main line of sub-surface FADs can be confirmed with the rope supplier.

Experience shows that the buoyancy typically used for subsurface FADs will stretch the rope up to an additional 5% and so this is what is used in calculations. An example is given below.

A subsurface FAD is being deployed at a depth of 500 m. The mooring section will use 16 mm multistrand polypropylene rope (which has 5% stretch). The anchor block used is 0.6 m high and there is 3 m of galvanised chain above the anchor, connecting it to the main line rope. Once deployed, you want the top of the buoyancy section to settle at 20 m below the surface.

$$MRL = d - ((a + c + b) + (stretch\% \text{ x } r))$$

$$MRL = 500 – ((20 + 0.6 + 3) + (0.05 \text{ x } (500 – (20 + 0.6 + 3))$$

$$= 452 \text{ m}$$

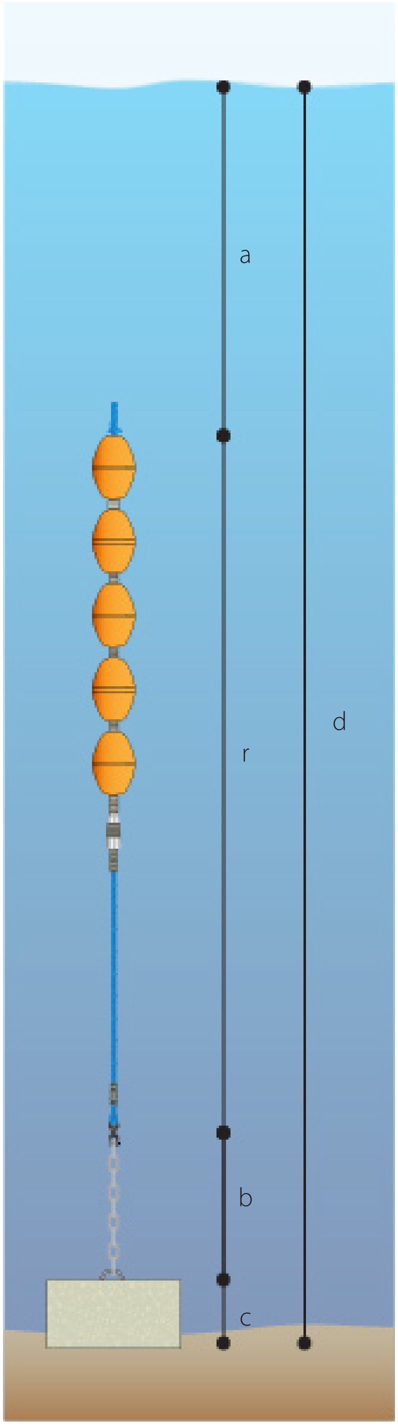

Figure 23. Diagram showing the components required for the calculation of subsurface main line rope length (a = floatation settling depth, b = chain length, c = block height, = deployment depth, r = main rope).

4.2.3 Combination rope main line

A combination of sinking and buoyant ropes is the most common main line system for anchored FADs, particularly those deployed further offshore, as the catenary curve provides elasticity in the system to enable the FAD to withstand the forces produced by waves and currents. The use of sinking rope at the surface also keeps the main line from floating on or near the water surface, thus reducing the chance of entanglement with boats and fishing gear.

The length of sinking (e.g. nylon) and buoyant (e.g. polypropylene) rope required to rig a catenary curve mooring depends on the deployment depth, the length of the catenary curve, the weight of the nylon rope and the buoyancy of the polypropylene rope used. Table 7 summarises the rope lengths required for FADs deployed with 16 mm rope from 50 m to 3,000 m depths.

Hardware

Hardware (swivels and shackles) has been identified as one of the weak points of anchored FADs across the region. As a result, there has been a shift away from the extensive use of hardware connectors, with a preference to splice or use knots for the connections between ropes (Figure 24). This has been aided by the increased availability of multistrand rope (which does not require the use of a swivel between the upper floatation and the main line). If three-strand rope is used, a swivel is required in the connection between the upper floatation and mooring system (e.g. see insert in Indo-Pacific design, Figure 6).

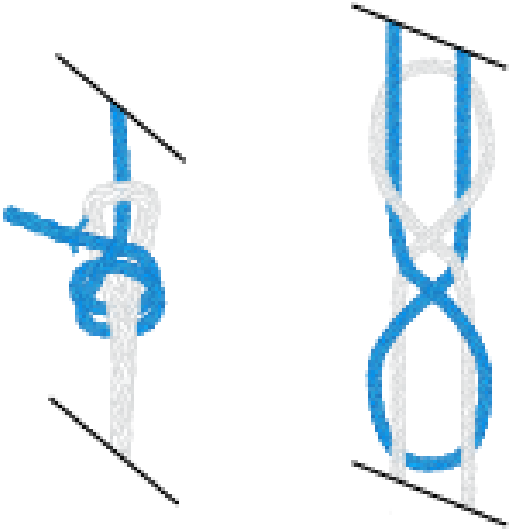

Figure 24. Diagram showing three options for connecting nylon and multistrand rope (left – double sheet bend; middle – monofilament carrick bend; right – splice).

Supplementary buoyancy

Supplementary buoyancy is required for FADs deployed in depths less than 1,500 m to lift the 3 m anchor chain and rope clear from the seabed to reduce the possibility of entanglement with any rocks or other substrate. The buoyancy and positioning of the supplementary floats is dependent on the deployment depth. Table 7 shows the total amount of buoyancy required, which can be made up by using multiple floats. For example, 21 L supplementary buoyancy can be made up of 2 x 11 kg buoyancy floats. It is important that the supplementary buoyancy floats have the appropriate working depth (which can be calculated from Table 7, column 5). It is recommended that centre-hole pressure floats, with a working depth twice their depth position, are used for supplementary buoyancy.

When rigging supplementary buoyancy, splice each float on a separate rope to the main line rope (Figure 25). It has been found that, due to the constant friction of the float against the main line, the supplementary buoyancy can damage it. The main line rope can be encased in plastic tubing and whipped, prior to the supplementary buoyancy being spliced to the mooring (as per Figure 19).

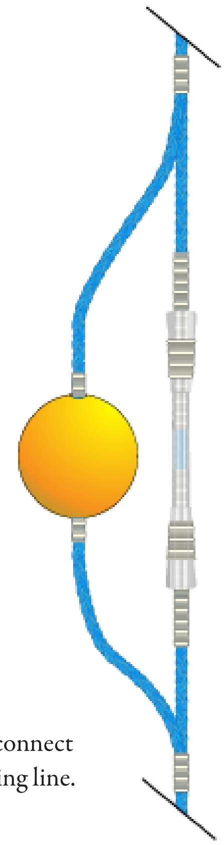

Figure 25. Diagram showing how to connect supplementary buoyancy to the mooring line.

Scope

As anchored FADs are anchored at one point, the upper floatation can swing around the anchor point in a circle, depending on tides and currents. The radius of this circle is referred to as the scope (Figure 26) and depends on the deployment depth and the total mooring lengths. The scope of a FAD is required for navigational purposes, particularly for offshore FADs, and the scope is usually required by maritime authorities, along with the FAD's deployment location. Scope is also important when deploying close to a coastline, as the gradient of the coast from the shoreline to the FAD anchor point may mean the sea floor ends up within the scope of the FAD, resulting in entanglement of the mooring line.

Scope is calculated using the depth and total rope length as:

$$\text{scope} = \sqrt{(\text{total rope length}^2 - \text{depth}^2)}$$

Table 7 provides the scope for different deployment depths using combination mooring system.

Where deployment is close to coastlines or where fishers use deep drop-stone fishing methods, the scope can be reduced by reducing the recommended additional length of rope down from 25% (as per Table 7) to 15% or 10%.

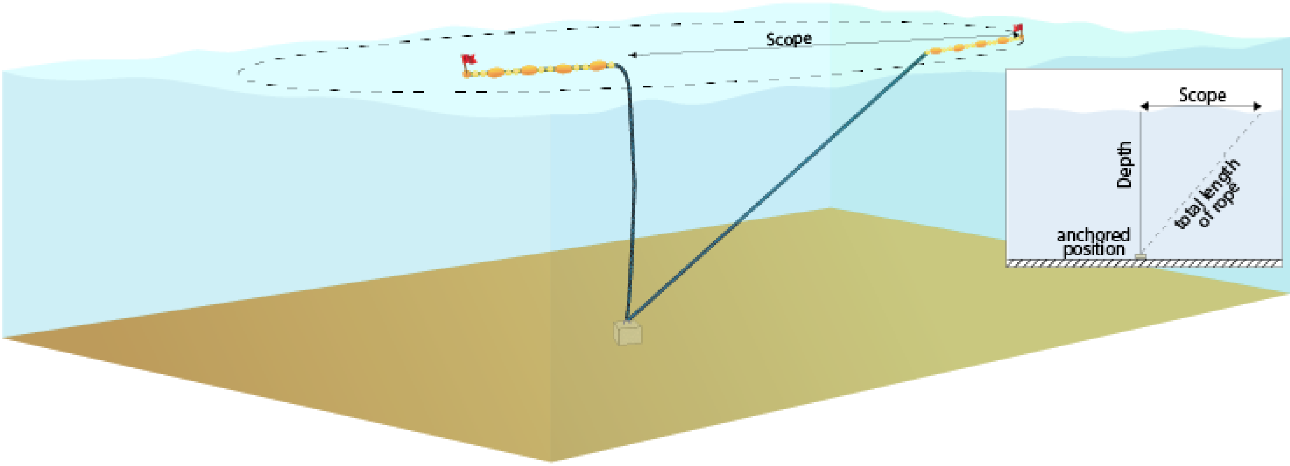

Figure 26. Diagram showing a FAD's scope.

Table 7. Rope lengths needed for FAD site depths from 50 m to 3,000 m.

Depth*	Total length of rope (m): Site depth + 25%	Length of nylon rope (m)	Length of polypropylene rope (m)	Minimum supplementary buoyancy (litres)	Distance of float from sea floor	Scope (m) radius from anchor
50	65	20	45	21	3–13	42
100	125	40	85	21	7–37	75
150	190	60	130	20	40–70	117
200	250	80	170	20	68–98	150
250	315	100	215	19	100–130	192
300	375	120	255	18	132–162	225
350	440	140	300	18	164–194	267
400	500	160	340	17	196–226	300
450	565	235	330	17	228–258	342
500	625	245	380	16	260–290	375
550	690	255	435	15	292–322	417
600	750	265	485	15	324–354	450
650	815	270	545	14	356–386	492
700	875	280	595	13	385–415	525
750	940	290	650	13	428–458	567
800	1,000	300	700	12	470–500	600
850	1,065	310	755	11	513–543	642
900	1,125	320	805	11	555–585	675
950	1,190	325	865	10	598–628	717
1,000	1,250	335	915	9	640–670	750
1,100	1,375	355	1,020	8	725–755	825
1,200	1,500	375	1,125	6	810–840	900
1,300	1,625	390	1,235	5	895–925	975
1,400	1,750	410	1,340	3	980–1,010	1,050
1,500	1,875	430	1,445	2	1,065–1,095	1,125
1,600	2,000	445	1,555	NO SUPPLEMENTARY BUOYANCY REQUIRED		1,200
1,700	2,125	465	1,660			1,275
1,800	2,250	485	1,765			1,350
1,900	2,375	500	1,875			1,425
2,000	2,500	520	1,980			1,500
2,100	2,625	540	2,085			1,575
2,200	2,750	555	2,195			1,650
2,300	2,875	575	2,300			1,725
2,400	3,000	595	2,405			1,800
2,500	3,125	610	2,515			1,875
2,600	3,250	630	2,620			1,950
2,700	3,375	650	2,725			2,025
2,800	3,500	665	2,835			2,100
2,900	3,625	685	2,940			2,175
3,000	3,750	705	3,045			2,250

* if deployment depth is in between, always use the deeper depth

4.3 Anchor technical considerations

In the past, massive cement block anchors were used for anchored FADs to ensure their holding power, even under intense waves and currents. These blocks were extremely heavy and required a large boat and winch for safe deployment. Over the past decade, the evolution of anchor system design has been driven by the need to find more cost-effective designs to enable deployment by small boats and in remote island locations.

Despite the desire for lighter anchors, anchor weight remains important and is dependent on the buoyancy of the upper floatation section of the FAD and the deployment depth. The anchor weight needs to be calculated so that the upper floatation cannot lift it, nor can the anchor slip on the seafloor as a result of current. As a rule, anchor weight (when in the water) should be at least three times the buoyancy. This is particularly important for sub-surface and offshore FADs (deployed at deeper depths). Nearshore FADs (<500 m depth) can have a reduced anchor weight (equivalent to buoyancy) if combined with a danforth or grapnel anchor.

4.3.1 Anchor types

FAD anchors can be made from a variety of materials, including concrete, steel or sandbags. Different types of anchors perform better than others, depending on a number of factors, including slope, bottom substrate and water depth. Other factors can also influence anchor choice, such as availability and small boat deployment. Common anchors used in the region are described below and Table 8 provides an overview of the recommended anchors to use, based on different parameters.

Table 8. Recommended anchor types for different parameters (■ = optimal; ■ = sub-optimal; ■ = ok, but not recommended; ■ = not appropriate).

	Anchor type						
	Large cement block*	Dual half drum	Smaller cement blocks	Sand bags	Danforth anchor	Grapnel	Reused steel
Steep slope	optimal (with gripping anchor)	sub-optimal (with rebars stabilisers)	optimal	sub-optimal (if sandy bottom)	optimal	not appropriate (unless rocky bottom)	optimal (with gripping anchor)
Coral/rocky bottom	optimal	optimal	optimal	not appropriate	not appropriate	optimal	optimal
Sand/mud bottom	optimal	optimal	optimal	optimal	optimal	not appropriate	optimal
Deep depth	optimal	sub-optimal	optimal	ok, but not recommended	optimal	not appropriate	optimal
Small boat deployment (min 23 ft)	ok, but not recommended (max 500 kg)	ok, but not recommended	sub-optimal	ok, but not recommended	optimal	optimal	ok, but not recommended (max 500 kg)
Ease of safe deployment*	ok, but not recommended	ok, but not recommended	ok, but not recommended	ok, but not recommended	optimal	optimal	ok, but not recommended

* Safe deployment possible for all anchors using a small barge (see section 5.3 Small barge deployments)

Large cement block

Large cement blocks are wide (typically 1.2 m x 1.2 m x 0.6 m), made with the correct mix of concrete, sand, aggregate and water (Image 2). The cement blocks are constructed with internal reinforcing and a steel anchor attachment point. Large cement block anchors are strong and heavy (underwater weight ~1120 kg) giving them a high holding power, even at deeper deployments. Cement anchors require 30 days' curing time before they can be deployed. Due to their size and weight, large boats with a crane or winch are required for deployment.

Image 2. Large cement block anchor being lifted by crane for deployment.

Dual half drum

The dual half drum anchor is constructed from a clean petrol drum cut in half and filled with cement (Image 3). Re-bars inserted through the sides of the drum act like stabilisers to stop them rolling if deployed on a slope. Using two drums (that are connected) reduces the weight of each individual drum, enabling the anchors to be lifted using a lift bar, rather than a crane or winch, although they remain quite heavy, so care must be taken when lifting. Prior to deployment, the two drums are connected using galvanised chain, and 30 days' cure time is also required for this anchor.

Image 3. Dual drum anchor showing the internal set-up (left) and prior to being deployed (right).

Small cement blocks

Small cement blocks follow the same concept of the large cement block design, except that the blocks are significantly smaller (~50 kg). Being smaller and lighter, they can be lifted by two people using a lift bar and can be deployed from small boats. The small cement blocks are joined with galvanised chain. Care needs to be taken in deployment to ensure that they are deployed as one unit. These anchors are usually deployed using a deployment table (Image 4). Ensure that the total number of blocks required for one FAD will fit onto the table.

Image 4. Anchor deployment table on a small boat showing multiple small cement blocks attached in series.

Danforth and grapnel anchor

Danforth and grapnel anchors are generally used as supplementary FAD anchors to increase the holding capacity and reduce the weight of the main anchor block (Image 5). Danforth anchors are a common, general-use fluke type anchor. They perform best in mud or sand, where the fluke digs into the sea bed and has strong holding power (20:1 weight to holding power ratio in sand and 9:1 in mud). A 25 kg danforth anchor is usually used, which has an equivalent holding power of ~500 kg in sand.

Grapnel anchors are light-weight anchors that can provide additional holding strength on certain substrates. These anchors perform best on rocky substrates, where one or multiple flukes grip the rock. The grapnel anchor does not perform well in sand or mud, as there is nothing for the anchor to grip onto. Grapnel anchors can be constructed by inserting and bending lengths of re-bar through a steel pipe and cementing them in place.

Image 5. A 25 kg danforth anchor (left) and a constructed grapnel anchor (right).

Recycled steel anchor

Anchors can be made from recycling old disused steel (e.g. engine blocks) that are located close to the proposed FAD deployment location. Such items are common across the Pacific, particularly in locations with limited refuse options. Due to the high density of steel, these anchors are lighter in air and often smaller than cement anchors. While recycled steel anchors significantly reduce the cost of a FAD, care must be taken to ensure that old engines are depolluted prior to deployment to avoid oil contamination. The calculation of anchor weights can also be a challenge (see 4.3.2 Anchor weight calculations).

Image 6. Anchor constructed from a recycled engine block.

Ultimately, the choice of anchor, or combination of anchors, will depend on a number of factors and different anchor types will perform better than others under different scenarios. Table 8 provides a guide on the performance of different anchors under different parameters.

Sandbag anchor

Sandbag anchors can be an option for FADs in remote locations where cement is not available and transport options are minimal. Bags are filled with sand, weighing ~20 kg each bag. The anchor is then made up of a series of connected sandbags (Image 7). Due to the low density of sand, the overall weight in air of all sandbags combined is much greater than cement anchors. Sandbag anchors are effective on sand but can be damaged quickly on rocky substrates. The Vatuika FAD design uses sandbags that have been specifically developed in Japan, using materials that are more resistant to decay.

Image 7. Anchor constructed from sandbags.

4.3.2 Anchor weight calculations

The weight of an anchor in the water is subject to Archimedes' principle, which states: *"an object immersed in a fluid is subjected to an upward force equal to the weight of fluid it displaces"*. This principle dictates whether an object sinks or floats and means that the weight of an anchor *under water* is less than its weight in air. The density of the materials the anchor is made of dictates the weight of fluid displaced and therefore its weight in water.

With the evolution of different materials being used for FAD anchors and different combinations of floats for the FAD upper floatation, FAD technicians need to be able to accurately calculate the weight of anchor required.

Based on Archimedes' principle, the underwater weight of an anchor can be calculated using the following formula:

$$\text{anchor weight}_{(\text{in water})} = \text{anchor weight}_{\text{air}} \times (\rho_{\text{anchor}} - \rho_{\text{seawater}})/\rho_{\text{anchor}}$$

(where *ρ=density*) and the density of seawater is 1025 kg/m^3. The approximate density of common anchor types is provided in Table 9.

Table 9. Approximate density of common anchor materials.

Anchor material	Density (kg/m^3)
Cement (varies, based on sand: gravel: cement ratio)	2,330
Steel	7,800
Sand	1,600

Note: If the anchor weight in air is unknown, it can be calculated by the anchor's volume and density using the equation:

$$\text{mass} = \text{volume}_{\text{anchor}} \times \rho_{\text{anchor}}$$

Example 1:
A cement block is 1.2 m wide x 1.2 m long x 0.6 m high. The density of cement is ~2,330 kg/m^3.

$$\begin{aligned}
\text{mass} &= \text{volume}_{\text{anchor}} \times \rho_{\text{anchor}} \\
\text{anchor weight}_{\text{air}} &= (1.2\ \text{m} \times 1.2\ \text{m} \times 0.6\ \text{m}) \times 2{,}330\ \text{kg/m}^3 \\
&= 0.864\ \text{m}^3 \text{ x } 2{,}330\ \text{kg/m}^3 \\
&= 2{,}013\ \text{kg}
\end{aligned}$$

$$\text{anchor weight}_{\text{in water}} = \text{anchor weight}_{\text{air}} \times (\rho_{\text{anchor}} - \rho_{\text{seawater}})/\rho_{\text{anchor}}$$

$$\text{anchor weight}_{\text{in water}} = 2{,}013 \times (2{,}330 - 1{,}025)\ /2{,}330$$

$$\text{anchor weight}_{\text{in water}} = 2{,}013 \times 0.56 = 1{,}128\ \text{kg}$$

Example 2:

Two half petrol drums, filled with cement. A petrol drum is 0.8 m high (so half a drum is 0.4 m high) and the inside drum diameter is 0.57 m.

$$\text{Drum volume} = \text{Volume of a cylinder} = \pi r^2 h$$
$$= \pi \times 0.285^2 \times 0.4$$
$$= 0.1\ m^3$$
$$\text{anchor weight}_{air} = (\pi \times 0.285^2 \times 0.4) m^3 \times 2{,}330\ kg/m^3$$
$$= 237\ kg\ \text{(per half drum)}$$
$$\text{anchor weight}_{in\ water} = 237 \times (2{,}330 - 1{,}025) / 2{,}330$$
$$\text{anchor weight}_{in\ water} = 237 \times 0.56 = 132.7\ kg\ \text{(per half drum)}$$

Example 3:

Calculation of recycled steel anchor

For the example of recycling an old steel engine block, the first step is to calculate the volume of the block, excluding the empty space (Figure 27). For example, an engine block is 1.2 m x 0.6 m x 0.5 m. It has six internal 'empty' cylinder spaces (0.6 m long, 20 cm in diameter). The volume of the block is 1.2 x 0.6 x 0.5 = 0.36 m^3. The volume of one cylinder is π x 0.012 x 0.6 = 0.019 m^3, so six 'empty' cylinders have a volume of 0.113 m^3. The total volume of the engine block is equal to 0.36 m^3 – 0.113 m^3 = 0.247 m^3.

$$\text{Anchor weight}_{air} = 0.247\ m^3 \times 7{,}800\ kg/m^3$$
$$= 1{,}926\ kg$$
$$\text{Anchor weight}_{in\ water} = 1{,}926 \times (7{,}800 - 1{,}025) / 7{,}800$$
$$= 1{,}926 \times 0.87 = 1{,}672\ kg$$

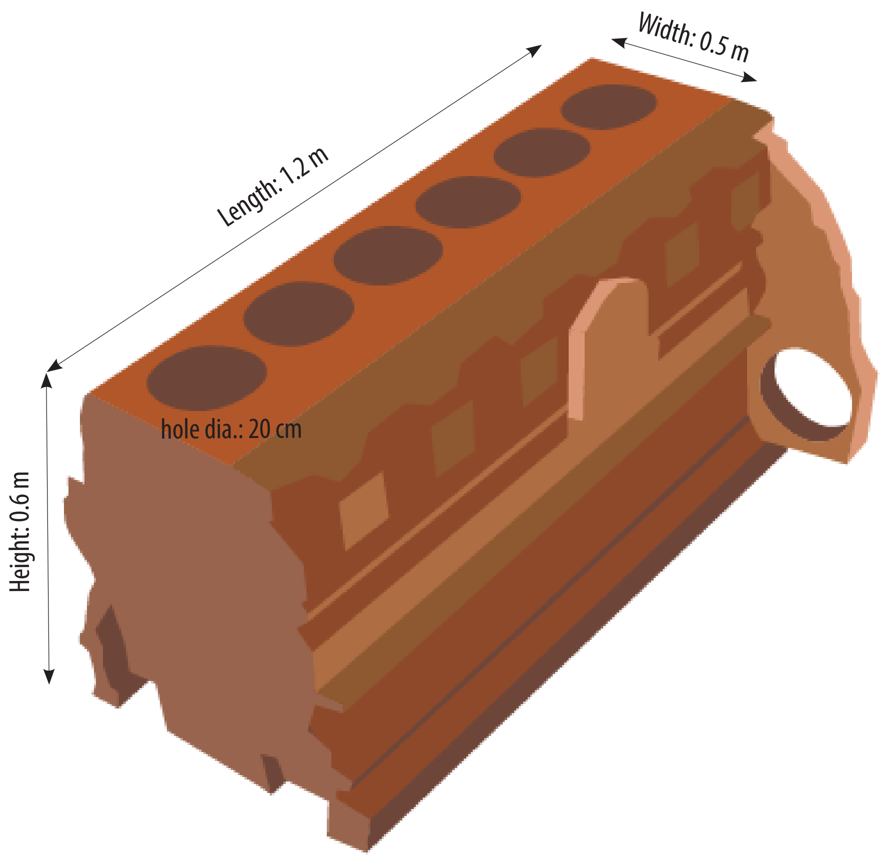

Figure 27. Example of calculating the volume of a recycled steel engine block anchor.

4.3.3 Anchor chain

Galvanised steel chain (16 mm) connects the anchor system to the main line. FADs that use a standard single block anchor with an additional danforth/grapnel anchor require 10 m of chain: 3 m above the anchor block (between the anchor and the main line rope) and 7 m between the anchor block and the gripping anchor.

If multiple (9) small blocks are used, a total of 10 m of chain is required: 3 m above the first block with 0.5 m between blocks and 3 m between the end block and the danforth anchor

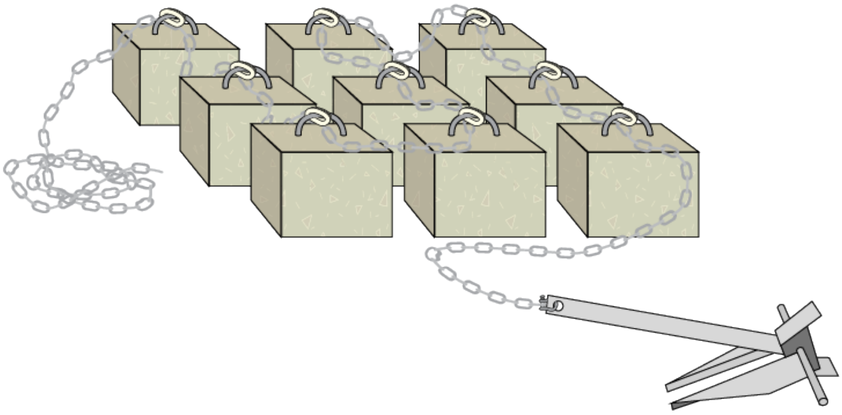

Figure 28. Diagrammatic representation on connecting multiple small blocks with galvanised chain.

4.3.4 Anchor chain and anchor block connections

The anchor chain is connected to the main line using a shackle and swivel (Figure 29). The swivel allows the rope to move with the current without twisting, while the chain prevents the rope getting tangled and rubbing against the anchor block. When attaching the main line to the swivel, ensure that the main line rope is protected from chafing by: whipping the main line rope along the section that goes through the swivel (Figure 29, left); encasing the rope in plastic tubing (Figure 29, centre); or using a thimble (Figure 29, right). The connection between the main line rope and swivel should be tight to restrict movement and chafing.

The swivel is then attached to the galvanised chain with a shackle. FAD technicians have experienced corrosion of the stainless-steel shackle locking pins, which can come loose. The locking pin should be secured by tying galvanised wire or thin rope through the eyelet of the locking pin and attaching that to the shackle, or spoiling the thread so that the locking pin does not come out.

The anchor chain is then connected to the anchor attachment point using a shackle. In the case of a cement block anchor, ensure that the steel rod used for the attachment point in the anchor is small enough for the chain and shackle to attach.

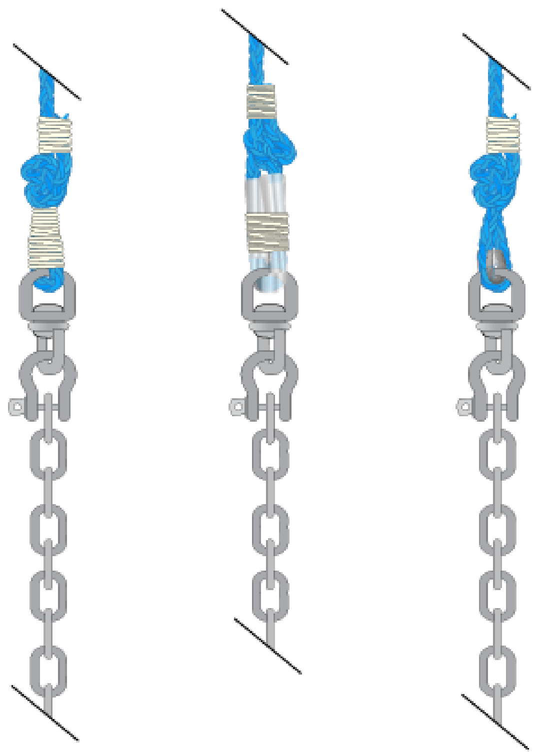

Figure 29. Anchor to main line rope connection.

4.3.5 Anchor weights for standard FAD designs

As described above, careful calculations are required to ensure that the anchor weight is sufficient to hold the total buoyancy of the FAD. The anchor weight (in water) should be at least three times the total buoyancy. However, due to safety concerns with lifting heavy anchors and the need to deploy FADs from small boats, when possible it is recommended to use supplementary techniques that mean the main anchor weight can be reduced.

Supplementary danforth anchors can be used for nearshore environments to enable a reduction in anchor weight. Danforth anchors have a holding power to weight ratio of 20:1 in sand and it is assumed that most of the substrates where FADs are deployed are sandy. In such circumstances, a 25 kg danforth anchor has an equivalent holding power of ~500 kg.

Table 10 provides the buoyancy, minimum anchor weight requirements, with and without using supplementary danforth anchors.

Table 10. Upper floatation buoyancy and anchor weights required for standard FAD designs (as per designs in this manual) with and without the use of a 25 kg supplementary danforth anchor.

		Bamboo (advanced)	Indo-Pacific (nearshore < 500 m)	Indo-Pacific (offshore)	Sub-surface	Lizard	NSW DPI (deep)
Buoyancy	Purse seine	-	5 x 7 kg	14 x 7 kg	-	4 x 7 kg	-
	ABS floats	1 x 24 kg, 1 x 11 kg	6 x 20 kg	15 x 20 kg	5 x 20 kg	8 x 20 kg	-
	Bamboo	3 x 3 m lengths (15 cm dia) or 50 kg buoyancy per 3 m length	-	-	-	-	-
	Special Mark (800 mm)	-	-	-	-	-	100 kg
Total buoyancy		155 kg	155 kg	398 kg	100 kg	188 kg	100 kg
Anchor weight without supplementary Danforth							
Minimum (in water) anchor weight (3 x buoyancy)		**465 kg**	**465 kg**	**1,194 kg**	**300 kg**	**564 kg**	**300 kg**
Anchor options (weight in air)	Cement	830 kg	830 kg	2,132 kg	535 kg	1,007 kg	535 kg
	Steel	530 kg	530 kg	1,372 kg	345 kg	648 kg	345 kg
	Sand	1,290 kg	1,290 kg	3,316 kg	833 kg	1,567 kg	833 kg

Anchor weight with supplementary 25kg Danforth

Minimum (in water) anchor weight		**155kg (plus Danforth)**	**155kg (plus Danforth)**	Anchor weights can be reduced with these FAD designs when using a supplementary danforth anchor. The reduction in anchor weight is, however, dependent on deployment depth and sea conditions (current, swell, etc.). FAD technicians need to take this into consideration and use their best judgement when reducing anchor weight for these FAD designs.
Anchor options (weight in air)	Cement	280 kg (plus danforth)	280 kg (plus danforth)	
	Steel	180 kg (plus danforth)	180 kg (plus danforth)	
	Sand	430 kg (plus danforth)	430 kg (plus danforth)	