PROPOSED ANCHORING SYSTEMS FOR GULF STREAM (GS) RENEWABLE ENERGY DEVICES ACCOUNTING FOR POTENTIAL OF GS MEANDERING

Md Ahsanuzzaman[1]
North Carolina State University (NCSU)
Raleigh, NC, USA

Mo Gabr
North Carolina State University (NCSU)
Raleigh, NC, USA
UNC Coastal Studies Institute
Wanchese, NC, USA

[1]Corresponding author: Email: mahsanu@ncsu.edu

INTRODUCTION

Gulf Stream (GS) current off the coast of North Carolina (NC) is a promising source of renewable energy. The energy from the GS in this case has the potential as a resource to supplement NC's increasing electricity needs. With the deployment of ocean current turbines, however, one of the initial steps is the selection of appropriate locations and the assessment of the electricity level that can be generated. Several experimental and modeling studies are currently on going at the University of North Carolina (UNC) Coastal Studies Institute that are targeted toward GS current resource characterization and environmental impact with the introduction of the energy converters.

The GS exhibits time-dependent lateral displacements (meanders) and location shift along its entire path. The meanders in the GS, stretching from the Florida Straits to Cape Hatteras, can potentially laterally shift the Stream as much as 40 kilometers from its mean position, with a standard deviation of 10 kilometers near Cape Hatteras [1]. The structure of the meanders inferred from sea surface temperature (SST) patterns found to be wavelike or eddylike and shifted at an average rate of 8 km/day [2]. Such meandering – with lateral variation in current velocities – has critical consequences on the magnitude of energy generation. A potential resource position for Gulf Stream turbines may be determined based on past monitoring and modeling data, but meanders may produce time periods with little or no energy production. Accordingly, if the GS is to become a viable energy option for the coast of NC, the issue of GS meanders need to be addressed. As a part of addressing the meandering issue, potential options for turbine locations are as follows:

Fixed at a Specific Location, with the understanding that there will be periods of time where no energy might be generated,

Fixed at Multiple Locations, which requires accurate forecasting of the locations with high current velocities and performing optimization to develop the needed number and distribution of turbines,

Movable turbines to track the areas with high velocities and abandoned areas where the velocities cease to be viable.

Objective and Scope

The goal of this study is to evaluate the turbines' anchoring foundation positioning strategies and cost while accounting for meanders in the Gulf Stream off the coast of NC. The scope of this research includes the following: (1) develop innovative and cost effective GS turbine anchoring options that address the meandering effect, and (2) build a spreadsheet model that automate the cost estimate for the various options. While this study is focused on the total cost of the anchoring foundation options, a companion study entitled "The Economics of Gulf Stream Energy off the North Carolina Coast" is focused on the levelized cost of energy with the anchoring options presented herein.

RESOURCE ASSESSMENT

The GS velocity data are predicted from a regional ocean circulation model entitled MABSAB [3]. The MABSAB model domain covers a horizontal grid resolution of 2 km and 36 vertical terrain layers [3]. The 2009-2013 MABSAB dataset used in this study includes 42 points within the reference GS domain of interest and provides hourly estimates of current velocity [4]. Annual frequency distributions of the current velocities are generated and the theoretical average annual GS energy generation at each location is calculated accordingly [4]. Figure 1A [4] illustrates the quality of each location based on generated average annual GS energy. Figure 1B [4] illustrates the probability of annual average current speed at each location.

The maximum and minimum energy are generated at locations RB3 and CL10, respectively. So, the potential site to deploy the turbine based on this data set is RB3 (34.58^0N, 75.26^0W) and the second most promising location is RB2 (34.69^0N, 75.47^0W). If only one location is used, then RB3 is selected. If more than one location is used for pre-deployment of multiple turbines or for movable turbines configuration, then both sites are considered. Proposed installation depth of the turbines is 75 meter from sea surface to avoid navigation and to overcome the additional loading effect due to surface waves and wind.

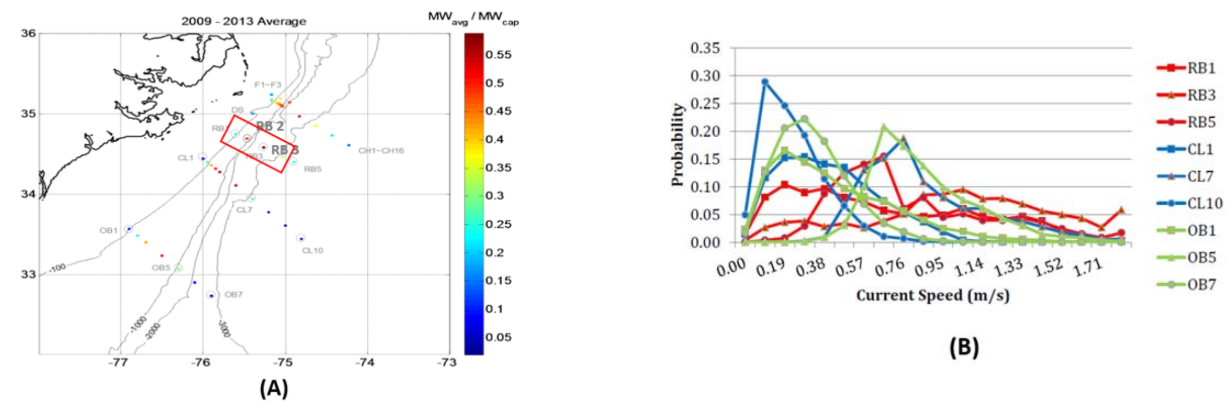


Figure 1. (A) ANNUAL AVERAGE ENERGY GENERATED IN EACH LOCATION BASED ON MABSAB DATA; (B) PROBABILITY DISTRIBUTION OF AVERAGE ANNUAL CURRENT VELOCITY [4].

OFFSHORE FOUNDATION TYPES IN VIEW OF GULF STREAM MEANDERINGS

Most prototypes of offshore foundation for renewable energy have borrowed ideas from offshore oil industry. Suction caissons, suction embedded plate anchors (SEPLA) and drag embedded anchors (DEA) are the main types of anchoring foundation considered herein given their ease of installment and considering that the depth of installation is in excess of 200 m [5]. These are briefly described herein.

Suction Caissons

The concept of suction caissons was first introduced to the offshore industry in 1980 in the Gorm field [6]. However, due to longer installation time and enormous initial costs, it was not developed for next ten years [6] until a field test demonstrated the installation feasibility of the dimensions needed to support the offshore oil infrastructure. Suction caissons, as illustrated in Figure 2A [8], are cylindrical piles with a sealed top and an open end with a valve located on top of the lid. The typical dimension of a suction caisson is 5-25 m in length with a length-to-diameter ratio (L/D) in the range of 3 to 6 [7]. The installation of a suction caisson in a clayey seabed is presented in Figure 2B. It is anticipated that suction caissons for renewable energy devices will have smaller aspect ratio compared to those deployed to support the offshore oil industry. This is due to the multiaxial loads and moment from such devices and the absence of a significant vertical compression loading. The installation of a suction caisson relies on own weight in addition to a net downward pressure, to push the caisson into to a substantial depth. Key factors which might influence suction caissons selection as preferred foundation for GS energy project include: reliable design methods, and ability of extracting and re-installing the foundation element. Removal in the case can be readily performed by reattaching the pumps and pumping water back into the bucket cavity, forcing it out of the seabed.

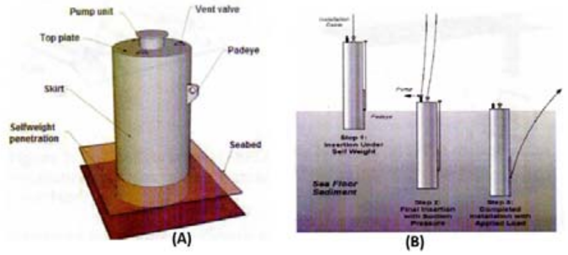


FIGURE 2. (A) SUCTION CAISSON CONFIGURATION (HTTP://WWW.OFFSHOREMOORINGS.ORG); (B) INSTALLATION PROCEDURE OF SUCTION CAISSON [8]

Suction Embedded Plate Anchor (SEPLA)

Suction Embedded Plate Anchors (SEPLAs) are large plates that are embedded into seafloor by using a suction caisson. Since 1988, SEPLA has been used as a foundation system in deep water installations (>2000 m) associated with oil and gas industry. SEPLA combines the advantage of suction caissons (i.e. known penetration depth) and vertically loaded anchors (VLA) (i.e. lower cost) while avoiding the disadvantage of imprecise positioning for VLAs [9].

The configuration of SEPLA is shown in Figure 3A [10]. The caisson is slotted vertically at its base, and the plate is placed vertically in the soil with a mooring chain attached to the plate. Once the chain is tensioned, the plate rotates until perpendicular to the pullout direction as shown in Figure 3B [11]. Imperfect Rotation can occur and the holding capacity of plate depends on the configuration of the anchor, seafloor composition, burial depth and loading characteristics. Key features which have the potential to influence to use of SEPLA for anchoring GS energy turbines include: easy to install at specific depth, resists uplift and lateral load, does not protrude above the seafloor, and can be placed onto moderate slopes. The installed anchors are typically not recoverable and are possibly susceptible to strength reduction due to the repeated nature of the loading.

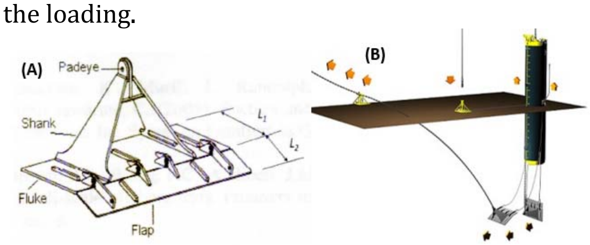


FIGURE 3. (A) SEPLA CONFIGURATION [10]; (B) SEPLA CONCEPT – SUCTION INSTALLATIONS, CAISSON RETRIEVAL, ANCHOR KEYING, & THE MOBILIZED ANCHOR [11].

Drag Embedded Anchor (DEA)

Generally, a drag embedded anchor (DEA) is composed of a wide fluke and thick shank connected with a mooring line at the shackle. To facilitate penetration, the configuration of the fluke includes two symmetric sharp triangular wedges in the direction of penetration [12] (see Figure 4A and 4B). The DEAs are functional in a broad range of seabed conditions and are usually employed as temporary anchorage with catenary mooring system in deep water to resist thrust force [12]. DEA's are not designed for resisting a large vertical load component; therefore, they are not typically suitable for a taut leg mooring system. DEA's are however recoverable and cost effective compared to other deep water anchors.

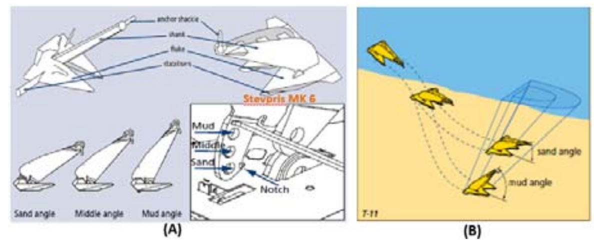


FIGURE 4. (A) DEA CONFIGURATION [12]; (B) INSTALLATION PROCEDURE OF DEA [12].

ANCHOR MOORING SYSTEMS

Mooring lines connect the floating structures with the anchors at seabed. Two types of mooring are mainly used: catenary moorings and taut leg moorings as illustrated in Figure 5 [5]. Catenary mooring is perfectly flexible suspended line. The weight of the line (made of synthetic material, metal, or combination) is utilized to reduce the stiffness of the mooring system and at the same time insuring horizontal or near horizontal pull on the anchors at seabed [5]. Catenary mooring is the most effective to resist lateral thrust force [5], albeit it requires a larger footprint area compared to the taut mooring. The anchor point of a taut leg mooring can resist both horizontal and vertical forces while a catenary mooring can resist mostly horizontal forces [5].

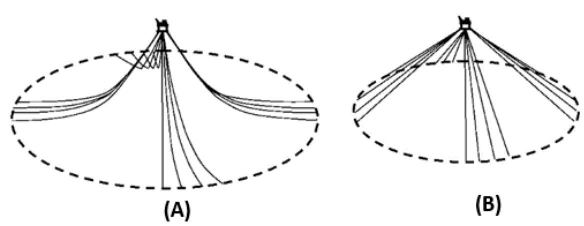


FIGURE 5. (A) CATENARY MOORING AND (B) TAUT LEG MOORING CONFIGURATION [5].

POTENTIAL FOUNDATION OPTIONS

The ocean current turbine prototype model for this study is selected from the proposed Reference Model 4 (RM4) developed by Sandia National Laboratories (SNL) [13]. The RM4 device has four rotors, a rotorless center nascelle and a straight 120 m long wing support frame. Each rotor has a diameter of 33 m and is reported having a capacity of 1-MW power [13] (yielding a total device rated power of 4 MW) (Figure 6A).

GS current near NC coast changes its flow direction seasonally and shifts laterally [1]. Therefore, a five-point mooring system is proposed for the modified RM4 model to resist multidirectional lateral forces and the potential for downward instabilities due to local eddies and current reversal within the water column. Modified RM4 consists of four taut leg mooring lines under tension (depending on buoyancy) and one catenary mooring is for thrust (Figure 6B).

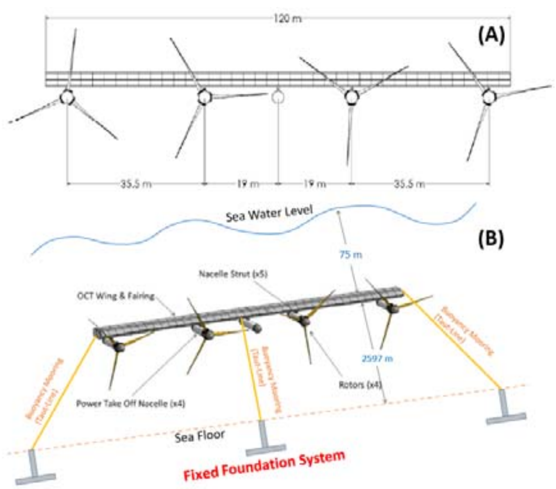


FIGURE 6. (A) DETAILS OF RM4 DEVICE; (B) FRONT OF MODIFIED RM4 MODEL [13].

Three potential anchoring foundation systems are proposed to address the issue of meandering: (i) fixed installation at a specific location, (ii) fixed installation at multiple locations and (iii) movable installation that can be performed within an area.

Fixed at One Specific Location Foundation System

Single or multiple units (10, 50 or 100 units) of turbines are considered in this study for the purpose of cost estimates. The assumption is deployment will occur at the most promising site from which current energy can be harnessed (i.e. RB3, Figure 1A). The main structural components for the fixed foundation system are: SEPLA, DEA, taut leg and catenary moorings (Figure 7A). Key features of this system include the use of cost effective SEPLA anchoring system and a single mobilization and/or demobilization cost.

Fixed at Multiple Locations Foundation System

This option includes pre-installation at multiple sites with the understanding that some of these sites will not produce a significant level of energy (or no energy) for a period of time. In this study, three potential locations between RB3 and RB2 were selected with 10 kilometers spacing. Key features of this system include same structural components as the fixed system (Figure 6A).

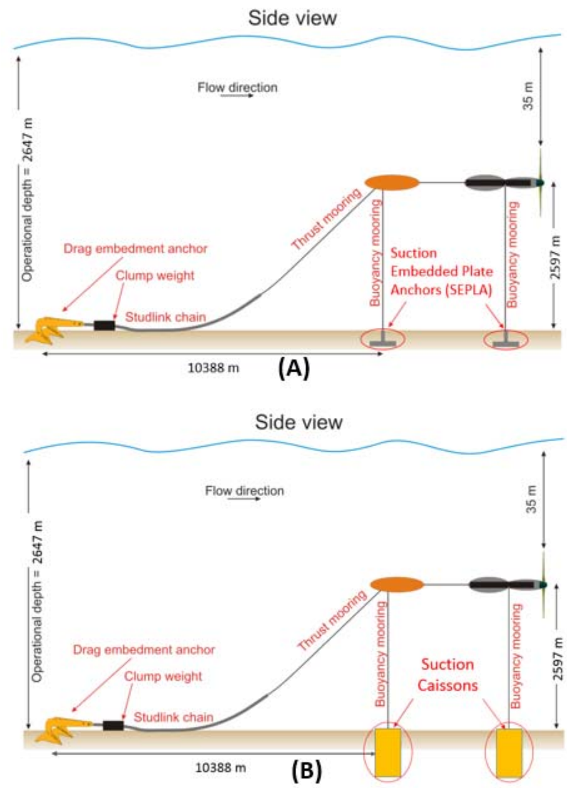


FIGURE 7. SIDE VIED OF (A) FIXED AND (B) MOVABLE FOUNDATION SYSTEMS-AFTER [13].

Movable Foundation System

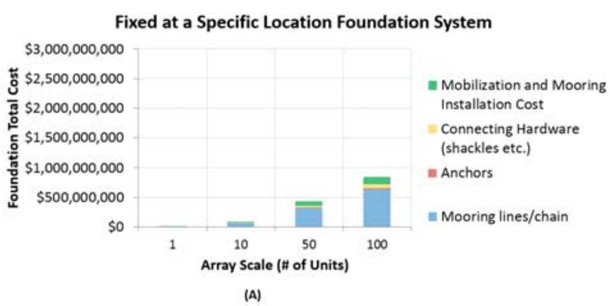
The main difference between fixed and movable foundation systems is the type of anchors to be used. Both suction caissons and DEAs (Figure 7B) are retrievable and reusable. Therefore, these are proposed at the two potential energy resource sites (RB3 and RB2, Figure 1A) with the idea that the turbines are move to the second site if the velocities at the first cease to meet the minimum requirement. However, there are several questions to be answered before such an option is considered viable. For example, what is the meanders magnitude and frequency and to what duration extent the new site will remain viable. The major cost component of repeated mobilization and demobilization will be added each time the system will be moved, and it is only viable if the cost of the energy production drop exceed the cost of mobilization and reinstallation.

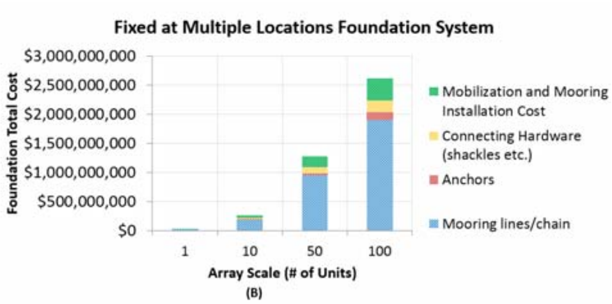
COST ESTIMATE – Cost Components

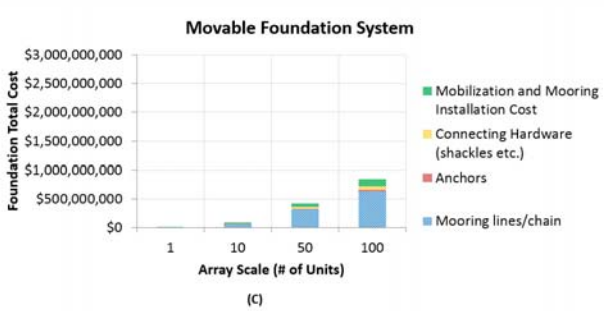
The primary cost components of each anchoring system include mooring lines/chains, anchors and connecting hardware [13]. Mooring lines/chains sub cost components [13] are: catenary (chain), taut leg (polyester) and studlink chain. Similarly, anchors sub cost components are: SEPLA, Suction Caisson and DEA. The uncertainties of the cost model input data include seafloor depth, distances among deployment sites, geologic hazards (such as salt domes or gas hydrates and extreme conditions (i.e. weather and earthquakes).

COST ESTIMATE – Cost Comparison

The main contribution of the total cost is the mooring lines/chain (Figures 8 A, B and C). The cost components increases non-linearly as the number of units is increased. Comparing the three foundation systems options proposed herein, the "fixed" foundations system is the least expensive. Followed by the movable option as shown in Figure 8D.







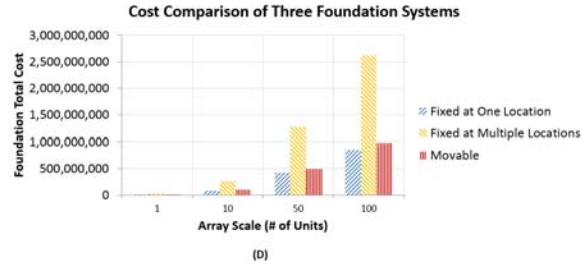


FIGURE 8. COST COMPONENTS OF (A) FIXED ONE SITE, (B) FIXED MULTIPLE SITES, (C) MOVABLE FOUNDATION SYSTEMS; (D) COST COMPARISON OF THREE FOUNDATION SYSTEMS.

The fixed at multiple locations option is the most expensive. This total cost is integrated into a system wide cost estimating model by DeCarolis et al. to assess the Levelized Cost of Electricity (LCOE). This work is present in a companion paper published in the same conference proceedings.

CONCLUSIONS

The work conducted in this study addresses the challenge of ocean current energy generation with the potential of the GS meanders, with a focus on the anchoring foundation system. Three proposed configuration are advanced to address this issue and the cost of each option is developed. Suction caisson and DEA with taut leg and catenary mooring lines are proposed for fixed and movable foundation systems. A movable system will consist of five-point mooring system, four suction caissons with taut leg moorings to resist buoyance tension and one DEA with catenary mooring line to resist thrust force from turbine. Such a configuration can provide stability in lateral direction during reversal of flow direction and current eddies.

The "fixed" foundations system is the least expensive, followed by the movable option and the fixed at multiple locations option is the most expensive. This total cost is integrated into a system wide cost estimating model by DeCarolis et al. to assess the Levelized Cost of Electricity (LCOE). Several challenges related to anchoring of GS turbines remain to be addressed. These include: (i) site specific meanders assessment which includes duration and frequency of meanders (ii) site specific geotechnical investigation to address geologic hazards which will influence the selected foundation type, and (iii) quantifying the impact of anchors and mooring lines on ecology and marine habitats.

ACKNOWLEDGEMENTS

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