Analysis of a Self-Propelled Dredger Capability in Shallow Waters Operation

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Abstract
This research presents a numerical and regressional analysis of a self-propelled trailing suction hopper dredger capability in Chanomi creek of 4m depth. The analysis considered using relation that express the payload, lightweight, deadweight, hopper capacity, work schedule, pump capacity, engine performance and sand density to determine the possible operation and duration of the excavation project based on the vessel cycle time. Using the regressional relationship, the dredger capacity was obtained and the result shows that a propulsive power of 678.75kW, bow thrusters power of 116.9kW and pump power of 540kW is needed for a 2324 tonnes hopper dredger capacity for the project. The result further revealed that the pump flow rate of 0.45m³/s per suction tube with a suction diameter of 0.338m is needed to fill the hopper capacity of 1000m³ for every 60 minutes. For a payload of 1356 tonnes, the reclamation operation requires 466trips for a one-year period. This provides an operational guide to operators in the sector on decision making and cost reduction operation.

Keywords – Dredgers, Pumps, Self-Propelled, Power, Pipelines

I. INTRODUCTION
Dredging is an excavation activity or operation usually carried out at least partly underwater, in shallow or deep seas or fresh water areas with the purpose of gathering up bottom sediments and disposing of them at a different location, mostly to keep waterways navigable or for reclamation. A dredge is a device for scraping or sucking the seabed, used for dredging, while a dredger is a ship or boat equipped with a dredge. The process of dredging creates spoils (excess material), which are conveyed to a location different from the dredged area. Dredging can produce materials for land reclamation or other purposes (usually construction-related). Dredging can create disturbance in aquatic ecosystems, often with adverse impacts (Environmental & Socio-economic) [1].

Hopper dredger is a self-propelled floating plant, which is capable of dredging material, storing it onboard, transporting it to the disposal area, and dumping it [2]. Hopper dredgers perform the largest and most dangerous jobs – clearing channels and offshore sandbars from the mouths of major rivers. Hopper dredgers move like a ship. When dredging, they move very slowly. When the dredger's hopper is loaded the dredge maneuvers both in and out of the channel to reach the relocation or dumpsite during this time, the dredger may move much faster and may turn frequently. Direct pump out is a common method of removing dredged material from hopper dredgers. A hopper dredger fills its hoppers as it dredges the bottom of the sea. The dredger then moors to a berth. Hoses connected to a pipeline extending to shore are attached to the hopper dredger discharge manifold [3]. The dredger mixes the dredged material with water to form slurry and pumps the slurry from its discharge manifold through the hoses and pipeline to a designated discharge location.

Dredging is needed generally to clear or ‘sweep’ water ways to make them navigable or to mine (in most cases) sand / sandstones for reclaiming land. Dredging is therefore an important infrastructural activity in the Niger delta region of Nigeria. While many waterways are being deepened or periodically dredged to maintain their depths, some other areas require sand filling / reclamation for construction of industrial and/or other major projects or facilities. For reclamation, the process requires dredging of suitable materials and depositing at designated location. This can sometimes present difficult challenges since the suitable material may not be found at the vicinity of the reclamation area. In the Niger Delta sand search shows isolated areas of rich deposits of suitable sand stones for sand filling for constructing major projects especially major Oil & Gas projects like Fertilizer plants, Tank farms, LNG plants etc.

A simple cutter and suction dredger, floating and land pipelines arrangement can readily achieve reclamation work at project locations. However, for reclamation of certain areas located remotely from appropriate sand deposits, there is a need to convey the dredge materials (Sand stones) by some other means (rather than by pipelines) and depositing at the required place. This requires the use of a self-propelled hopper dredger (SPHD).
The SPHD is a free sailing vessel and does not hinder other shipping during dredging and is therefore ideal for dredging in harbors and shipping channels inshore as well as offshore. The seagoing vessels are very suitable for borrowing sand under offshore conditions (wind and waves) and large sailing distances. The dredged material is dredged, transported and discharged by the vessel without any help from other equipment. (De) mobilization is very easy for this type of dredger. It can sail under its own power to every place in the world. Suitable materials for the SPHD to dredge are soft clays, silt sand and gravel [4]. Firm and stiff clays are also possible but can give either blocking problem in the drag head and/or track forming in the clay. In that case the drag head slips into foregoing tracks, resulting in a very irregular clay surface. Dredging rock with a SPHD is in most cases not profitable. It requires very heavy drag heads with rippers and the productions are rather low. All dredgers except the trailing suction hopper dredgers are stationary dredgers, which mean they are anchored by wires or (spud) poles.

There are few industrial activities today that involve such exposure to abrasion and consequent component wear as dredging [5]. The equipment does its work in one of the most unforgiving environments in the world. The material to be dredged is almost always abrasive, sometimes extremely so, the high levels of production, necessary mean high flow rates and huge stresses, and the working conditions do not favor simple solutions.

Although systems for describing dredgers vary, in general three broad classifications are recognized based on the means of excavation and operation. These are known as mechanical dredgers, hydraulic dredgers and hydrodynamic dredgers briefly explained above. Trailing suction hopper dredgers (SPHDs) also explained in brief above is classified as hydraulic dredgers [6]. Hydraulic dredgers include all dredging equipment which makes use of centrifugal pumps for at least part of the transport process of moving the dredged materials, either by raising material out of the water or horizontally transporting material to another site.

SPHDs are used on a wide variety of maritime construction and maintenance projects. These range from maintenance dredging of ports and access channels to remove sand to bring them to necessary depths to capital dredging projects such as giant land reclamation projects that require millions of cubic meters of sand [7]. The performance efficiency of a SPHD has a direct influence on the costs of a project. Consequently, research and development on SPHDs is an ongoing Endeavour to improve cost-effectiveness. The reason we are considering a SPHD fit for the purpose of dredging the Chanomi creek is to achieve these advantages listed.

1. Deepen the access channel and maintain a required depth for international trade navigation.
2. The dredged materials (Sandstones) will be used to reclaim lands for major projects in this case by the Escavos estuary.

A. Pumps and drive systems

Pump and drive systems cover all dredging hardware that physically move the dredge mixture. The cost-effectiveness of dredging today depends to a great extent on the performance of pumps; dredge pumps, submerged dredge pumps and jet pumps; and targeting the efficient transport of either the dredging mixture or water. They are critical components in almost all dredging systems. Their capacity has to be adapted to the task in hand, and their effective operating life in often difficult operating conditions maximized. Capital design, reducing the effects of wear, and ensuring easy repair and replacement all play key roles in upgrading efficiency and minimizing overall lifetime costs [8].

Inboard dredge pumps are the primary power source for transporting the mixture to the hopper or discharge location. Submerged dredge pumps in suction pipe offer the combined facility of lifting mixture cost-effectively from great depths and at higher output. High efficiency pumps are totally redesigned pumps created to minimize flow resistance and wear, and increase productions efficiency.

Jet pumps ensure high-pressure water for effective bottom soil loosening at the drag-head and hopper discharge. High efficiency pump design has been optimized to upgrade pump production and suction characteristics, and reduce wear, though this necessarily involves a higher investment than in the case of conventional pumps [5]. The logic behind the development of high efficiency pumps was that a marginal improvement in pump efficiency creates a huge multiplier effect on improving the cost effectiveness of production and reducing the length of the dredge cycle. Ongoing research into yet further ways of improving pump performance is a permanent element of all design efforts.

B. Framework of a SPHD

SPHDs or hoppers are self-propelled ships that contain a hopper or hold inside their hulls. They are primarily used for dredging loose material such as sand, clay or gravel. The main features of a SPHD are drag heads, suction pipes, swell compensators and gantries [1]. Typically, a SPHD is equipped with one or two suction pipes to which the drag heads are attached. A drag head is often compared to a giant vacuum cleaner. The suction pipes are lowered underwater and the drag heads are “dragged” over the seabed, sucking up material as the ship slowly moves forward, i.e., trails.
The suction pipes and drag heads can be positioned according to the performance needs of the intended dredging operation so that they can be transported to the hopper [9]. Through a pump system the sand/water mixture, called slurry, is drawn upwards to the hopper or hold of the vessel. Gantries and winches operate the suction pipes, moving them either overboard or bringing them back inboard. A swell compensator is used to control the contact between the drag head and the seabed when dredging in waves. In addition, the SPHD must have an overflow system to separate the slurry and discharge excess water. The efficiency of each of these elements will have a direct effect on the productivity of the SPHD [4].

Although all SPHDs have drag heads attached to suction pipes, drag heads can differ. The job of the drag head is to excavate the seabed material and to mix this material with water to create slurry. The drag head is the first “touchdown” place for contact with the soil [10]. In general, the force that makes the points of the drag head penetrate the soil is the weight of the drag head and the suction pipe. When dredging hard soils, however, if the weight is not sufficient, the drag head will not penetrate enough and will drag on top of the surface without cutting the soil. This results in a low mixture density which lowers the production of the hopper dredger. The higher the density of the mixture created by the drag head, the better the performance.

Continuing research has resulted in the development of drag heads that excavate with high pressure water jets assisted by teeth. They loosen the material and increase the productivity to form the slurry. To improve the efficiency of the water jets, sometimes the nozzle is integrated into the points of the drag head so that the water jets cut the soil moments before the point penetrates the soil. As a result, the forces needed to penetrate the soil are reduced, and the cutting efficiency is increased. The suction power of the pump then captures the seabed material and allows the slurry to be transported hydraulically. The sediment is hydraulically transported through suction lines by the centrifugal pump into the hopper [11]. There the solids settle out and are held awaiting transport and subsequent placement.

A more recently developed drag head is “the ripper “, a drag head with teeth. Usually rock is dredged by a cutter suction dredger (CSD), equipped with a special head that bores through hard material. But when sea conditions are rough, or a waterway has high vessel traffic, a cutter is not suitable. A ripper drag head can be placed on a traditional SPHD, and combines cutting power of a CSD with the flexibility and stability of a SPHD.

SPHDs are very flexible and can operate independently of other equipment and, since they are self-propelled, are able to transport the dredged material over long distances. Once fully loaded, the vessel sails to the unloading or placement site where the dredged material is offloaded [9]. Depending on the type of project, the dredged material will be offloaded / discharged in one of three ways: material is either deposited at the placement site by opening its bottom doors (hatches). Discharging through bottom doors allows quick, direct and total offloading of dredged material at a selected location. This is a reliable and effective method, but only in certain specific circumstances. During large land reclamation or beach nourishment projects, the SPHD will navigate to a selected borrow area, which may be many kilometers away from the construction site. At the borrow site the dredger will load up its hopper with sand and then sail to the site where new land is being built.

This material is then either rain bowed into place or pumped on site through floating or submerged pipelines. To connect the pipeline to the vessel requires a special link known as the bow coupling. If the distance from ship to shore is rather long, then booster pumps as an extra source of power can be added along the pipeline. The nozzle for rain bowing is also a part of the bow coupling [12].

A submerged pipeline is less sensitive to weather conditions, and provides no obstacle to other ships that may be crossing in the area. It is usually assembled on shore and then pulled out until the open end is positioned correctly on the beach. Sections may be added if necessary. Floating pipelines, although more sensitive to rough seas, have the advantage that they are visible above the surface of the water and can be reached easily if in need of repair.

II. MATERIALS AND METHODS

A. Adaptive Design of SPHD for Chanomi Creek Application

The required production capacity is expressed in m³/week or m³/month or even cubic meters per year. Besides that, insight required about the expected average cycle time of the trailing suction hopper dredger on the different jobs, as well as the type of soils to be dredged. Then the production capacity can be translated to:
The required payload in ton mass.
The maximum hopper volume in m³.  

The design of a dredge installation includes the determination of the required main dimensions and required powers of the following dredging components:

- Number of suction pipes
- Pump capacities
- Suction and discharge pipe diameter (m)
- Type of dredge pump
- Sand pump drive and power (W)
- Type and size of drag head(s)
- Hopper shape
- Discharge system

**B. Case Study Workability**

Design a Trailing Suction Hopper Dredger that can dredge 200,000m³ coarse sand and gravel at 31.5km (17Nm) from point of discharge.

- The dredger works 5 days at 12 hours per week
- Bunkers will be taken in the weekends
- Overhaul is 2 weeks in a year
- Weather delays is 3 weeks in a year
- Workability is 95%
- Christmas is 1 week.

**C. Particulars:**

Given the requirements and constraints stated above, the main particular of the vessel analyzed is shown in Table 1

**Table 1: Dredger Types Particular [1]**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Easy Dredge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Overall</td>
<td>81.75m</td>
</tr>
<tr>
<td>Length bpp</td>
<td>79.80m</td>
</tr>
<tr>
<td>Beam</td>
<td>15.80m</td>
</tr>
<tr>
<td>Depth</td>
<td>5.90m</td>
</tr>
<tr>
<td>Draft on dredging mark</td>
<td>5.50m</td>
</tr>
<tr>
<td>Hopper Capacity</td>
<td>2700m³</td>
</tr>
<tr>
<td>Loading capacity</td>
<td>4,320t</td>
</tr>
<tr>
<td>Diameter of suction pipe</td>
<td>1 X 500mm</td>
</tr>
<tr>
<td>Dredging depth</td>
<td>5-15m</td>
</tr>
<tr>
<td>Dead weight</td>
<td>4100t</td>
</tr>
<tr>
<td>Laden speed</td>
<td>11.5kn</td>
</tr>
<tr>
<td>Density of Sand</td>
<td>1.6T/m³</td>
</tr>
<tr>
<td>Power and Speed</td>
<td></td>
</tr>
<tr>
<td>Dredge pump</td>
<td>940kw</td>
</tr>
<tr>
<td>Main engines</td>
<td>2 X 1,250kw</td>
</tr>
<tr>
<td>Jet pump</td>
<td>360kw</td>
</tr>
<tr>
<td>Bow thrusters</td>
<td>385kw</td>
</tr>
<tr>
<td>AC Diesel Gen set for main</td>
<td>2 X 200kw</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total power</td>
<td>4,585kw</td>
</tr>
<tr>
<td>Laden speed</td>
<td>11.5 knots</td>
</tr>
<tr>
<td>Total storage space of diesel oil</td>
<td>220 m³</td>
</tr>
<tr>
<td>Total storage space of fresh water</td>
<td>30 m³</td>
</tr>
<tr>
<td>Accommodation</td>
<td>8-12</td>
</tr>
</tbody>
</table>

1. Main Particulars and Theoretical Formulation

**Displacement** \( \Delta = L \times B \times D \times C_{L} \times F_{p} \) \(^{[1]}[13]\)

Given that Vessel length = 60.0m, Block Coefficient = 0.9, Beam = 12.0m, Depth = 4.0m, Draft = 3.5m

\( \Delta = 60 \times 12 \times 3.5 \times 0.9 \times 1.025 \) = 2,324.7 Tonnes

- **Operations Specification**
  i. Reclamation of 10 hectares of swamp approximately 100,000m³
  ii. Depth of fill = 2m
  iii. Distance from sand deposit to fill area = 31.5km = 17Nm
  iv. Period of work = 5 days/12 hours, Bunkers at weekends
  v. Overhaul = 2 weeks /year
  vi. Holidays (Christmas) = 1 week.

- **Cycle Time**
  i. Distance to dredge site = 31.5km = 17Nm
  ii. Vessel Speed = 11.5Knot = 11.5Nm/hour
  First estimate of dredge cycle:
    i. Sailing to dredge area = \( \frac{17Nm}{11.5} \) = 1.48 hours
    ii. Loading of sand = 1.0 hours
    iii. Sailing to dump site = 1.48 hours
    iv. Unloading = 1.0 hours
    **Total time /Cycle** = \( 2 \times 1.48 \) + 2 = 5.96 hours
    Approximately = 6.0 hours

- **Required Load Trip**
  i. Available hours \( = [52 - 3] \times 5 \times 12 \) = 2,940 hours
  ii. Effective hours \( = 0.95 \times 2,940 \) = 2,793 hours
  iii. Number of trips/year \( = \frac{2793}{6} \) = 465.5 = 466
  iv. Available volume/trip = 900m³
  v. In coarse sand and gravel minimum filling of hopper = 90%
  vi. Required Hopper volume \( = \frac{900m^3}{0.9} \) = 1,000m³
  vii. Payload/Trip = 900 x 1.5 = 1350 Tonnes

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Trip Management
Since time taken to complete one cycle of trip = 6 hours. This means each day of 12 hours crew can handle 2 trips. The implication of which is that the total cycle will be completed in $\frac{466}{2}$ days = 233 days. Payload per trip
$= 1350$ Tonnes
Payload/day (12 hour)
$= 2700$ Tonnes
Required/ Tonnage of Sand
$= 200,000 \times 1.5$
$= 300,000$ Tonnes
Number of days required to deliver 300,000 tonnes of sand for reclamation
$= \frac{200,000}{2700} = 111.1111$ days
Number of weeks
$= \frac{111.1111}{5} = 22.22$ weeks
Number of months
$= \frac{22.22}{4} = 5.5$ months

2. Deadweight and Lightweight Relationship
To estimate the deadweight, we considered the crew and their possession, consumer goods, spare parts, ballast water and payload.

$Y = 3E - 06X^2 + 0.5586X$
where $Y$ is the lightweight and $X$ is the payload or cargo weight

Capabilities of the Dredger
i. Hopper (cargo capacity) = $900 \text{m}^3 = 1350$ Tonnes
ii. Sand Density = $1.5 \text{ Tonnes/m}^3$

Displacement in Tonage $\Delta_T = \text{Lightweight + Deadweight}$

Therefore, for a given value of payload $X = 1350$ Tonnes.
$Y = -3 \times 10^{-6} \times (1350)^2 + 0.5586 \times 1350$
$= -5.4675 + 754.11$
$Y = 748.6425$ Tonnes
Lightweight = $Y = 748.6425$ Tonnes
Recall that Deadweight = $W_d = 1.05X$
We know that $X = 1350$ Tonnes,
Hence Deadweight = $1.05 \times 1350 = 1417.5$ Tonnes

<table>
<thead>
<tr>
<th>$\Delta_T$ = Light weight + Deadweight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_T = y + W_d$</td>
</tr>
<tr>
<td>$(748.6425 + 1417.5)$ Tonnes</td>
</tr>
<tr>
<td>$2166.1425$ Tonnes</td>
</tr>
</tbody>
</table>

Compare with particulars; where displacement; $\Delta_p$
$= 2324.7$ Tonnes

Figure 1 Plot of Lightweight against Deadweight [7]

Figure 2 Plot of Weight against Displacement in Tonnes for Light and Dead Weights [7]
III. RESULTS AND DISCUSSIONS

A. Propulsion and Machinery Analysis

The analysis of the SPHD is tailored to maintain two main engines for both propulsion and dredging (i.e. also used to drive the pump). The configuration entails and gearing system that connects the propeller on one end and the pump on the fly-wheel end. This is feasible since the propulsion system is on sleep mode when the dredger is at work, with only the bow thruster used for the navigation. Based on the mathematical calculations deduced, the following results were obtained:

The result show that the main propulsion power is 543kW, but was validated with an efficiency of 80% to compensate for mechanical losses and the effect of external current. The final power after validation was 678.75kW however from the engine catalogue the closes rating that agreed with validation is a power of 746kW. The Bow Thruster Power was 81kW, but was validated with an efficiency of 70% to compensate for mechanical losses and the effect of external current. The final power after validation was 116.9kW however from the engine catalogue the closes rating that agreed with validation is a power of 129kW.

The result of the Pump analysis gave us a pump power of 540kW but was validated with an efficiency of 75% to compensate for mechanical losses and the effect of bends. The final power after validation was 746kW which highlights the possibility of also using the main propulsion engine to drive the pump and from the engine catalogue the closes rating that agreed with validation is a power of 129kW.

The analysis further shows that at a block coefficient $C_b$ of 0.9, the theoretical displacement of the ship was determined and used as a guide to ensuring that other hydrostatic parameters will bring about a matching specification as it relates to the stability. The block coefficient of a ship is the ratio of the underwater volume of the ship to the volume of a rectangular block having the same overall length, breadth and depth (draft). Using the block coefficient, the vessel displacement of 2,324 Tonnes and the design was considered with a 0.73% error margin.

Also, further analysis also revealed that from the Hopper capacity of 900m$^3$, the required hopper size to be provided in the dredger gives = 1000m$^3$. Hence the matching pump to fill this capacity in 60 minutes was a pump capable of delivering a flow rate of 0.45m$^3$/s per suction tube, from which we obtained a suction diameter of 0.338m. Using a pump selection catalogue, the matching pump rating for this selection was found to be 540kW, recall that to compensate for losses, we chose to drive the pump with the main propulsion Engine of 746kW, which has already compensated for a pump efficiency of 75%.

Based on the foregoing, the following load and trip management we have that

- Payload/trip = 900m$^3$ x 1.5 = 1350Tonnes
- Time taken to complete one round trip is 6 hours approximately. This implies that two trips can be covered in one working day of 12 hours.
- About 466 trips are needed to complete the reclamation project in one year, which gives 233 days will be numbers of days this dredger will work to complete the project, which is 5.2 months or approximately 6 months.
- That the carry capacity of the dredger if increased (Hopper =1350 tonnes)/trip = 2700 tonnes/day will deposit 300,000 tonnes of Sand; the dredger will work in 300,000/2700 days = 111.111 days = 22.222 weeks = 5.55 weeks. Approximately 6 months.

IV. CONCLUSION

This research work considered the feasibility of using the SPHD in the Niger Delta region of Nigeria, for the canalization of the narrow and shallow creeks towards making them deep enough for the international maritime business in Exploration and Exploitation of its vast and rich resources. The application of the preliminary analysis to ascertain the vessel operational capacity at Escravos terminal through which reclamation of the island can be achieved in a short time provide a vital information for various company players.

However, based on sand search statistics, the Chanomi creek (10-17) nautical mile away from the Escravos terminal hold the same type of sand stone required to hold the project, but as the available of the SPHD, the project can be handle despite the shallow and narrow Chanomi creek. The analysis further shows:

i. That the turnaround time of dredging and depositing from the Chanomi creek is safer, faster and more secure than dredging from the Lekki area.
ii. That a smaller shallow draft SPHD is feasible and required for the rapid development of the Niger delta.

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