FEASIBILITY STUDIES
ON
OFFSHORE WIND DEVELOPMENT IN INDIA

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National Institute of Ocean Technology,
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Chennai.

MNRE Stakeholders consultation meet, 14th August 2013
OUTLINE

- Introduction
- Global Scenario
- Offshore Wind Resource Assessment
- Commercial Viability - India
- Design Philosophy of Substructure
  - Static Analysis
  - Code Checking
  - Free Vibration Analysis
  - Earthquake Analysis
  - Coupled Hydrodynamic and Aerodynamic Analysis
- Conclusion
Why Offshore Wind Energy?
- Wind speeds are stable and high
- Significant Potential in India.
- Most of the potential onshore sites already utilized
- Coastal Areas are best benefitted less transmission Coast
- Low Noise Pollution and Visual Intrusion
E V O L U T I O N  O F  O F F S H O R E  W I N D  P R O J E C T S

➢ First Offshore Wind Turbine – Sweden (1990)
  ▪ 220 kW – Single, 250m from the coast @ 7m Water Depth.
  ▪ Supported on Tripod
➢ First Offshore Wind Farm – Denmark (1991)
  ▪ 450 kW – 11 Turbines, 1.5 – 3 km from coast @ 2-6 m Water Depth
  ▪ Gravity Foundation.
➢ Global Installed Capacity - 5.5 GW

Current Status - Europe
➢ Under Construction 14 Farms → 3.3 GW
➢ Planning Phase 7 Projects → 1.2 GW
➢ Future Plans
  ▪ 1.4 GW in 2013
  ▪ 1.9 GW in 2014
  ▪ Total 40 GW by 2020

Source: European Wind Energy Association (EWEA)
Offshore Wind Farm Installations in Europe

- **Nysted (165.2 MW)**
- **HornsRev I (160 MW)**
- **Middelgrunde (40 MW)**

**EUROPEAN SCENARIO**

- Down Trend
  - High Construction Cost
  - Unexpected failures
    - Extreme wind
    - Extreme waves

- 293 Turbines (1166 MW)
REST OF WORLD

- **China**
  - Largest onshore wind power developer
  - 5 GW by 2015 -- 30 GW by 2020

- **USA**
  - 2nd largest Onshore developer. But, no Offshore Projects till date
  - Approved project – 468 MW at Massachusetts
  - 10 GW by 2020 -- 54 GW by 2030

- **Japan**
  - First offshore wind farm 16 MW - 2004
  - 1 GW by 2020

- **India**
  - Onshore
  - Offshore – Policy being formulated

Installed Capacity - India

- Thermal: 67%
- Hydro: 8%
- Wind: 2%
- Nuclear: 1%
- Bio-mass: 2%
- Solar: 0%
OFFSHORE WIND RESOURCE ASSESSMENT

- Based on Winds derived from satellite data
- Wind Speeds for 10 years (18-07-1999 to 17-11-2009)
- One observation for each day at 10m above sea surface - scaled to 80m
- Data validated using 5 moored buoys (ESSO-NIOT)

Sites Considered

- Gujarat
  1. Jakhau
  2. Navalakhi

- Tamil Nadu
  1. Rameshwaram
  2. Kanyakumari

Monthly climatology's of Wind Power Density at 80 m
**Wind Speed Distribution**

Inter-annual variation of wind for 10 years

- Scaled to 80m → Power Law
  \[
  \frac{V_{\text{ref}}}{V_x} = \left(\frac{Z_{\text{ref}}}{Z_x}\right)^{0.14}
  \]
  - \(V_{\text{ref}}\) = Velocity at ref. height
  - \(V_x\) = Velocity at Hub height
  - \(Z_{\text{ref}}\) = Reference Height (10 m)
  - \(Z_x\) = Hub Height

CDF of wind speeds at 10m and 80m

Wind speed distribution at 80m
Power Production for Various Turbines

Rameshwaram

Kanyakumari

Jakhau

Power Curve
3.0 MW

Wind Speed (m/s)

Power (kW)

0 5 10 15 20 25

Wind Speed (m/s)

0 1000 2000 3000 4000

Rameshwaram

Kanyakumari

Jakhau

Pie Charts for Various Turbines

Re-Power-R122-3.0MW

Re-Power-R126-5.0MW

Re-Power-R122-3.0MW

Legend:
- Idle
- 0% - 25% MW
- 25% - 50% MW
- 50% - 75% MW
- 75% - 100% MW
- Full Capacity

Percentage of Operation Time:
- Rameshwaram: 63%
- Kanyakumari: 71%
- Jakhau: 45%
## Plant Load Factors

### Power Curves

![Power Curves Graph]

<table>
<thead>
<tr>
<th>Legend</th>
<th>Capacity (MW)</th>
<th>Dia. (m)</th>
<th>Turbine Properties</th>
<th>Plant Load Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cut in</td>
<td>Rated</td>
</tr>
<tr>
<td>Turbine 1</td>
<td>1.5</td>
<td>82</td>
<td>4</td>
<td>14</td>
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<tr>
<td>Turbine 2</td>
<td>2.1</td>
<td>88</td>
<td>4</td>
<td>14</td>
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<tr>
<td>Turbine 3</td>
<td>2.1</td>
<td>95</td>
<td>3.5</td>
<td>12</td>
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<tr>
<td>Turbine 4</td>
<td>2.1</td>
<td>97</td>
<td>3.5</td>
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<tr>
<td><strong>Turbine 5</strong></td>
<td><strong>3</strong></td>
<td><strong>122</strong></td>
<td><strong>3</strong></td>
<td><strong>11.5</strong></td>
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<tr>
<td>Turbine 6</td>
<td>3.4</td>
<td>104</td>
<td>3.5</td>
<td>13.5</td>
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<tr>
<td>Turbine 7</td>
<td>5</td>
<td>126</td>
<td>3.5</td>
<td>14</td>
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</tbody>
</table>
Components Effecting Investment Cost

- Capital Cost
  - Super structure
    - Turbine
    - Installation
  - Sub Structure
    - Foundation
    - Installation
  - Electrical Equipment
    - Collection System
    - Integration system (Sub station, Switch gears, Generator and etc…)
    - Transmission (Sub station to Power grid)
    - SCADA/EMS
  - Development and Permits

- Operation and Maintenance
VARIOUS SUBSTRUCTURE CONCEPTS

Share of support structures in different wind farms

Gravity-based < 10 m
Monopile (10 – 30m)

Tripod (20 -50 m)
Jacket (30 -60 m)
Floating Platforms (> 60 m)
Parameters

- **Capital Cost:**
  - Formulae given by Dicorato et al, 2011
  - 25% Equity and 75% from Bank (14% interest)

- **Operation and maintenance:**
  - Formula given by Bernd et al, 2012

- **Electricity unit price in Tamil Nadu:** Rs 2.51 per kWh

- **RECs:** Rs. 1500 per MWh

- **GBI:** Rs.0.50 per kWh with a cap of Rs. 1crore per MW
## Commercial Viability

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Onshore</th>
<th>Offshore</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Rameshwaram</td>
<td>Kanyakumari</td>
</tr>
<tr>
<td>1</td>
<td>Capital Cost (Cr.)</td>
<td>6.71</td>
<td>13.79</td>
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<tr>
<td>2</td>
<td>Insurance (Cr.)</td>
<td>0.17</td>
<td>0.56</td>
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<tr>
<td>3</td>
<td>O &amp; M (Cr.)</td>
<td>3.46</td>
<td>13.84</td>
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<tr>
<td>4</td>
<td>Interest (Cr.)</td>
<td>2.82</td>
<td>9.12</td>
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<tr>
<td>5</td>
<td>Total Expenses (Cr.)</td>
<td>13.16</td>
<td>37.30</td>
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<tr>
<td>6</td>
<td>Total income (Cr.)</td>
<td>19.91</td>
<td>47.07</td>
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<tr>
<td>7</td>
<td>Net Profit (Cr.)</td>
<td>6.75</td>
<td>9.77</td>
</tr>
<tr>
<td>8</td>
<td>Generated Power (kWh in Cr.)</td>
<td>4.20</td>
<td>10.38</td>
</tr>
<tr>
<td>9</td>
<td>IRR (%)</td>
<td>13.82</td>
<td>14.45</td>
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</tbody>
</table>

### Cash Flow - Onshore

![Cash Flow - Onshore](chart-onshore.png)

### Cash Flow - Kanyakumari

![Cash Flow - Kanyakumari](chart-kanyakumari.png)
**Methodology for Substructure Development**

<table>
<thead>
<tr>
<th>External conditions</th>
<th>Loads</th>
<th>Support structure design</th>
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</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Aerodynamic loads</td>
<td>Blade and Tower</td>
</tr>
<tr>
<td>Earthquake</td>
<td>Seismic loads</td>
<td></td>
</tr>
<tr>
<td>Waves &amp; current</td>
<td>Hydrodynamic loads</td>
<td>Substructure</td>
</tr>
<tr>
<td>Soil</td>
<td>Soil structure interaction</td>
<td>Foundation dynamics</td>
</tr>
</tbody>
</table>
OVERVIEW

- Basic Loads
  - Aerodynamic Load on Rotor
    - IEC 61400
  - Wind Loads on Structure
    - IS 875 Part iii
  - Wave Kinematics
    - Stokes 5th order
  - Hydrodynamic
    - Morison Equation
  - Earthquake
    - IS 1893 Part iv

- Load Combination
  - Extreme Wind Load during Cyclone
  - Earthquake during operation of Turbine

- Pile Soil Interaction
  - 3 Orthogonal Nonlinear Springs (API RP 2A WSD)
  - Soil at Palk Strait
## LOADS CONSIDERED

### Methods for Load Calculation

<table>
<thead>
<tr>
<th>S.No</th>
<th>Method</th>
<th>Benefit</th>
<th>Challenges</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Use available standards like IEC, DNV, ABS, GL etc.</td>
<td>Simplified method</td>
<td>Needs more number of assumptions</td>
<td>Simplified method gives approximate loads</td>
</tr>
<tr>
<td>2</td>
<td>Use suitable Tools for loads prediction</td>
<td>More accurate &amp; gives detailed data</td>
<td>Getting the Tool, Learning &amp; execution</td>
<td>Involves more time &amp; Cost</td>
</tr>
<tr>
<td>3</td>
<td>Approach OEM’s for Transfer Functions</td>
<td>More accurate &amp; gives detailed data</td>
<td>Getting from OEM’s</td>
<td>Involves more time &amp; Cost</td>
</tr>
</tbody>
</table>

### Properties of Wind Turbine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Diameter (m)</td>
<td>((\text{Power}/310)^{1/2.01})</td>
</tr>
<tr>
<td>Blade Length (m)</td>
<td>((\text{Rotor diameter}) / 2.08)</td>
</tr>
<tr>
<td>Blade Mass (kg)</td>
<td>(2.95 \times (\text{Blade length})^{2.13})</td>
</tr>
<tr>
<td>Design Rotational Speed (rpm)</td>
<td>15</td>
</tr>
<tr>
<td>Max Rotational Speed (rpm)</td>
<td>(1.5 \times \text{Design Speed})</td>
</tr>
<tr>
<td>Distance between CG of blade &amp; Rotor centre</td>
<td>(\frac{1}{2} \times \text{Blade Length})</td>
</tr>
</tbody>
</table>
**Wind / Hydrodynamic Load on Tower and Substructure**

- **IS 875 Part – 3**
  - Basic Wind Speed (Survival), $V_b = 39$ m/s
  - Basic Wind Speed (Operational), $V_b = 9$ m/s

- **Hydrodynamic Loads**
  - | Parameter               | Environment | Normal | Extreme |
    |------------------------|-------------|--------|---------|
    | Wave Height ($H_s$)    | 2 m         | 4 m    |         |
    | Wave period ($T_p$)    | 7 s         | 12 s   |         |

- **Earthquake Loads**
  - IS 1893 – 2002 (Response Spectrum Method)
  - Zone Factor, $Z = 0.1$ (Zone II)
  - Reduction Factor, $R = 2.0$ (Steel Chimney)
  - Importance Factor , $I = 1.5$ (Steel Chimney)
  - Percentage of damping = 2 %
## Pile Soil Interaction

<table>
<thead>
<tr>
<th>Description</th>
<th>Graphic Log</th>
<th>Depth (m)</th>
<th>Scale</th>
<th>SPT (N-Value)</th>
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</thead>
<tbody>
<tr>
<td>Grey fine sand</td>
<td></td>
<td>3.0 m</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0 m</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Grey silty fine sand</td>
<td></td>
<td>4.5 m</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.5 m</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Grey silty clay with pieces of calcareou sand</td>
<td></td>
<td>3.0 m</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>crushed of rock and of calcareous sand stone</td>
<td></td>
<td>10.6 m</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Crushed pieces of rock and of calcareous sand</td>
<td></td>
<td>1.5 m</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>stone</td>
<td></td>
<td>12.0 m</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Silty fine sand</td>
<td></td>
<td>1.5 m</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Fine sand with white color small stone</td>
<td></td>
<td>3.0 m</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.6 m</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Fino Silty sand</td>
<td></td>
<td>4.5 m</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>21.0 m</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEPT H (m)</th>
<th>Internal Friction $\Phi^o$</th>
<th>Skin Friction (KPa)</th>
<th>Tip Resistance (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>32</td>
<td>1.99</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>3.99</td>
<td>0.22</td>
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<td>4.5</td>
<td>33</td>
<td>4.69</td>
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<tr>
<td>6</td>
<td>37</td>
<td>7.99</td>
<td>0.43</td>
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<tr>
<td>7.5</td>
<td>39</td>
<td>9.99</td>
<td>0.54</td>
</tr>
<tr>
<td>9</td>
<td>33</td>
<td>9.39</td>
<td>0.39</td>
</tr>
<tr>
<td>10.5</td>
<td>34</td>
<td>10.96</td>
<td>0.45</td>
</tr>
<tr>
<td>12</td>
<td>44</td>
<td>24.19</td>
<td>2.16</td>
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<tr>
<td>13.5</td>
<td>31</td>
<td>14.09</td>
<td>0.58</td>
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<tr>
<td>15</td>
<td>41</td>
<td>24.84</td>
<td>2.16</td>
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<td>16.5</td>
<td>41</td>
<td>27.32</td>
<td>2.38</td>
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<tr>
<td>18</td>
<td>42</td>
<td>29.81</td>
<td>2.59</td>
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<tr>
<td>19.5</td>
<td>34</td>
<td>25.97</td>
<td>1.40</td>
</tr>
<tr>
<td>21</td>
<td>35</td>
<td>27.97</td>
<td>1.51</td>
</tr>
<tr>
<td>30</td>
<td>34</td>
<td>32.40</td>
<td>2.00</td>
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</table>
## Substructure Concepts

<table>
<thead>
<tr>
<th>Wind Turbine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power, MW</td>
<td>3</td>
</tr>
<tr>
<td>Hub Height, m</td>
<td>80</td>
</tr>
<tr>
<td>Rotor Diameter, m</td>
<td>96</td>
</tr>
<tr>
<td>Tower Diameter, m</td>
<td>4.5</td>
</tr>
<tr>
<td>Tower Thickness, m</td>
<td>0.05</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Monopile</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth, m</td>
<td>10</td>
</tr>
<tr>
<td>Monopile Diameter, m</td>
<td>4.2</td>
</tr>
<tr>
<td>Monopile Thickness, m</td>
<td>0.06</td>
</tr>
<tr>
<td>Monopile Length, m</td>
<td>30</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Jacket</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth, m</td>
<td>30</td>
</tr>
<tr>
<td>No. Jacket Legs</td>
<td>4</td>
</tr>
<tr>
<td>No. of Braces</td>
<td>3</td>
</tr>
<tr>
<td>Slope of Jacket Legs</td>
<td>1 in 10</td>
</tr>
<tr>
<td>Platform level, m</td>
<td>35</td>
</tr>
<tr>
<td>Jacket Leg Diameter, m</td>
<td>1.8</td>
</tr>
<tr>
<td>Jacket Pile Diameter, m</td>
<td>1.6</td>
</tr>
<tr>
<td>Pile and Leg Thickness, m</td>
<td>0.05</td>
</tr>
<tr>
<td>Brace Diameter, m</td>
<td>0.4</td>
</tr>
<tr>
<td>Brace Thickness, m</td>
<td>0.015</td>
</tr>
</tbody>
</table>
**Results – Static Analysis**

**Deflected Profiles**

- **Monopile - 0° & 45°**
  - Deflections < Permissible Value
  - 1.25% of Tower height (i.e. 1 m)

- **Jacket- 0°**
  - Length: [m]
    - Min: 0.001
    - Max: 0.90

- **Jacket- 45°**
  - Length: [m]
    - Min: 0.0006
    - Max: 0.704
RESULTS – STATIC ANALYSIS

Code Checking

Monopile - 0° & 45°

Jacket - 0°

Jacket - 45°

Code Checking – API Standards

Utilization Factor < 1.0 (Safe)
Free Vibration Analysis

- Regular wave periods ➞ 6 to 30s.
- Natural Frequencies

<table>
<thead>
<tr>
<th>Mode No</th>
<th>Monopile</th>
<th></th>
<th>Jacket</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (Hz)</td>
<td>Period (s)</td>
<td>Frequency (Hz)</td>
<td>Period (s)</td>
</tr>
<tr>
<td>1 &amp; 2</td>
<td>0.23</td>
<td>4.19</td>
<td>0.41</td>
<td>2.4</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>1.87</td>
<td>0.53</td>
<td>1.51</td>
<td>0.64</td>
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<tr>
<td>5</td>
<td>5.78</td>
<td>0.17</td>
<td>3.07</td>
<td>0.32</td>
</tr>
</tbody>
</table>

- Safe against resonance - Waves.

Earthquake load Analysis

- Earthquake during Turbine operation
- Response Spectrum Analysis
- The Member utilization factors are less than 1.0.
- Deflection at the top of the nacelle 0.52 m
Dynamic Analysis for Wave and Wind

Forcing Functions

- Time - Hydrodynamics
- Time - Aerodynamics
- Time - Hydrodynamics
- Time - Aerodynamics

Response

- Time - Displacement
- Time - Displacement
- Time - Displacement
- Time - Displacement

Animation
OFFSHORE PLATFORM FOR COLLECTING WIND AND METEOCEAN DATA
**DATA COLLECTION PLATFORM**

**Platform Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Legs</td>
<td>4</td>
</tr>
<tr>
<td>No. of bracings</td>
<td>4</td>
</tr>
<tr>
<td>Platform level</td>
<td>15 m</td>
</tr>
<tr>
<td>Pile Length</td>
<td>10 m</td>
</tr>
<tr>
<td>Water Depth</td>
<td>10 m</td>
</tr>
</tbody>
</table>

**Instrumentation**

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>No. of Legs</th>
<th>No. of bracings</th>
<th>Platform level</th>
<th>Pile Length</th>
<th>Water Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Velocity</td>
<td>Lidar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Direction</td>
<td>Lidar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave</td>
<td>Wave Rider Buoy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>current</td>
<td>ADCP, RCM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tide</td>
<td>RTG, ATG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PH, Salinity &amp; TSS</td>
<td>Water Quality buoy</td>
<td></td>
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</tbody>
</table>
INSTALLATION SEQUENCE

Transportation in Barge

Launching using crane Barge

Option – 1: Piling through Jacket legs

Placing Template

Piling driving through template

Jacket on piles

Pile connection

Quick coupling – To connect piles to jacket

Option – 2: Piling through legs with follower
Lidar for Wind Assessment

Working Principle:
- Laser radiation scatters from atmospheric aerosols
- A laser is focused at a point incident with the aerosols
- Aerosols movement follows the wind
- Scattered radiation is ‘Doppler’ shifted by the wind speed
- The ‘in-line’ component of wind speed is measured

Lidar can Provide:
- Wind profiling across heights from 10 m to 200 m (i.e. hub height, tip height measurements and beyond)
- Both vertical and horizontal wind speed components
- Turbulence intensity measurements

Advantages of Lidar:
- Minimized safety risks due to removal of working at height (Mast)
- Rapid installation in hard to reach areas – forested sites, helicopter drop zones
DYNAMIC RESPONSE OF STRUCTURES
DURING CONSTRUCTION AND IN PLACE

Jonswap(Hs)
Significant Wave Height(Hs) :0.5
Peak enhancement Factor :3.3
Peak wave Frequency :10s

Spectral Density (m²/s)
Period (s)

Actual Condition
Simulated Condition

mnre_2.mp4
**CONCLUSIONS**

- Wind Resource Assessment indicates feasibility of offshore wind farms development in Tamil Nadu (Rameshwaram, Kanyakumari) and Gujarat (Navlakhi, Jakhau).
- Variability of wind potential observed within the states. Kanyakumari with PLF of 0.71 and Rameshwaram of 0.63, whereas Jakhau has low PLF of 0.45 for 3MW Turbine.
- Initial substructure concept analysis indicates Monopile/Gravity substructures are suitable. However, NIOT working on suction bucket foundation also.
- Commercial viability studies indicate IRR of 16.8 at Kanyakumari and 14.5 at Rameshwaram, which needs confirmation after offshore measurements.
- A pilot project can be taken by NIOT with the support of MNRE
- Since, NIOT is working on Ocean Technology, its services can be utilized for offshore wind development in terms of feasibility study, design of substructure / sub sea cables and demonstration of projects.
THANKS FOR KIND ATTENTION