Stability analysis and design of offshore submerged breakwater constructed using sand filled geosynthetic tubes

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Abstract

Kadalur Periyakuppam (KPK) is a fishing village located 70 km south of Chennai in Tamil Nadu. The coastline of KPK was subjected to severe erosion due to high energy waves during Thane (2011), Nilam (2012) and Madi (2013) cyclones. The Tamil Nadu Fisheries department facilities located near the coast is subjected to damage as the coastline has receded by 45 m in the last few years following the severe erosion caused by cyclones. Since most of the erosion occurred after the storm waves hit the shoreline, sustainable option for shoreline protection would be to shift wave breaking to deeper depths. Based on numerical model studies and assessment of shoreline behaviour over two years, it is proposed to construct a submerged segmented breakwater. The submerged breakwater is proposed to be constructed at 4 m water depth up to a height of 3.5 m using sand filled geosynthetic tubes. Geosynthetic tubes shall be placed in a stacked manner with 2 tubes of 1.5 m high each at the bottom and a tube of 2.5 m height at the top accounting for height loss due to settlement. Design and stability checks are carried out by using available literature as no standard methods or design codes are available for design or stability checks for the geosynthetic tubes. The breakwater structure is checked for stability against sliding, overturning and bearing capacity. The geosynthetic tube material specifications such as tensile strength, ultra violet ray resistance, apparent opening size and fabric material are calculated using suitable design methods. The scouring, in front and behind the breakwater structure under prevailing wave conditions, is estimated for designing scour protection.

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1. Introduction

National Institute of Ocean technology (NIOT), Chennai has proposed to install a submerged segmented shore parallel breakwater at 4 m water depth at Kadalur Periyakuppam, Tamil Nadu. It is proposed to use sand filled geosynthetic tube for the construction. The design of material properties of geosynthetic tubes, stability of the sand filled geosynthetic tubes under wave loading and scouring action near the tube are discussed in detail in this paper.

1.1. Background

Shoreline erosion is a major threat to coastal infrastructure. Erosion results from natural or man-made causes. Natural geomorphologic evolution in the form of erosion can occur due to prevailing wave climate, water levels, currents etc. Human interventions with the coastlines such as construction of breakwaters, seawalls are also likely to result in large-scale erosion. One of the important natural causes is the waves breaking on the shore. These waves become furious and cause severe damage during cyclones. In the last few years, the east coast of India is frequently affected by cyclones, the major ones being Thane (2011), Nilam (2012), Madi (2013) and Hud Hud (2014). Study area, Kadalur Periyakuppam (KPK) is located south of Kalpakkam (between 12°26′57″N and 12°26′14.2″N). KPK comprises three fishing villages immediately south of Palar River and north of a creek as shown in Fig. 1. A number of fisheries facilities have been developed by Tamil Nadu Fisheries Department on the coast of KPK, which is found to severely erode during cyclones. Accretion occurring in the following calm season is not sufficient to regain the lost beach. The net erosion has caused scouring below the fisheries structures and beach loss as shown in Fig. 2. The extent of the KPK shoreline requiring protection is about 1.5 km long comprising of three villages.

Fig. 1. Location of KPK

1.2. Detached submerged breakwater

The design of a coastal protection measure needs to consider stabilizing the coastline in a long-term and protection of the shoreline from the effects of storms. Also, it should not cause changes to the adjacent coastline or transfer the problem to nearby areas. Long term studies by agencies like the USACE indicate that conventional shore protection measures like groins, breakwaters, seawalls, revetments, bulkheads, beach-fill, etc., have certain disadvantages like blocking of long shore sediment transport resulting in severe erosion to the down-drift side, scouring near toe of revetments etc. In the case of a shore-parallel breakwater, which is placed near the shoreline to protect a beach-fill or placed offshore and designed to intercept a portion of long shore moving sediment, it is likely to perform well for various coastal environments (CERC-90-15(1990)).
Detached breakwaters are constructed at a significant distance offshore of the original shoreline so that they reduce the incoming wave energy to produce a calm region on the landward of the structure (CERC-90-15(1990)). The beach response may be either a salient or tombolo based on structural and environmental parameters such as structure length, distance offshore, transmissibility, wave climate, etc. Submerged breakwaters are a type of detached breakwaters constructed with a low crest elevation, therefore allowing a smaller amount of wave energy into the protected area. The beach response to these types of structures is usually a salient. The key purpose of these low crested structures is to reduce the wave action on the coastline and to maintain its dynamic equilibrium (Pilarczyk (2003)).

Detailed field and hydrodynamic model studies have been conducted and it is proposed to install a submerged segmented shore parallel breakwater at 4 m water depth (Sivakholundu et al. (2014)) with seven breakwater segments. The length of each breakwater segment is 200 m, the gaps between the segments are 60 m and the breakwater height is 3.5 m which is decided based on hydrodynamic model studies (kiran et al. (2014)).

2. Design of geosynthetic tubes

Geosynthetic tubes are extensively used for shore protection in the form of sea walls, groins or breakwaters. These tubes are placed in required position and filled hydraulically or mechanically with locally dredged material to the designed height. If the required height of the structure is not achieved by a single tube, tubes are placed in stacked manner. Use of Single tubes with very high tensile strength, which can achieve up to 3 m height on filling, reduces the overall cost of project and reduces workload. The shortage of the traditional construction materials like rock has increased the usage of geosynthetic tube technology (Oh and Shin (2006)). In case of any adverse impact of the structure on the shoreline, it can be easily removed unlike conventional methods using hard materials. Because of the flexibility of the material, it can adjust according to the bed profile during filling and stabilize once the excess water flows out of the tube.

Geosynthetic tubes for submerged breakwater construction should be designed for resisting stresses while filling (placing) and under the mentioned environmental conditions in Table 1. The aperture opening should be optimum so that soil is retained and water is drained out during filling.

2.1. Design of geosynthetic material strength

The main design parameter of geosynthetic tubes are the tensile strengths in circumferential and longitudinal directions and the seam strength. These parameters have to be designed considering the pressure conditions occurring during placing and filling by pumping slurry. Degree of sand filling in geosynthetic tubes in the breaker zone have to be around 60% or higher to avoid failure due to sand migration called as caterpillar mechanism (Van Steeg and Bezuijen (2010)). Methods used to determine the strength values include a) Liu, Goh, and Silvester
given in Pilarczyk (2000) b) Timoshenko method given in Bezuijen and Vastenburg (2013) and c) GeoCoPS software. For design purpose, the geosynthetic tubes are assumed to be filled on land as it provides conservative estimate when compared to submerged condition. Design inputs are provided in Table 2.

| Parameter                | Value   |
|--------------------------|---------|
| Depth                    | 4 m CD  |
| Tide                     | 1 m     |
| Surge                    | 1 m     |
| Storm Wave height        | 4 m     |
| Significant wave height  | 3 m     |
| Mean wave period         | 6 s     |
| Peak Wave period         | 10 s    |

Table 1. Environmental Parameters adopted for design

| Parameter                | Value   |
|--------------------------|---------|
| Circumference of tube    | 15 m    |
| Required height after filling | 2.5 m |
| Fill Ratio               | 0.78    |
| Unit weight of slurry    | 13 kN/m³|
| Unit weight of soil      | 18 kN/m³|
| Unit weight of sea water | 10.10 kN/m³|
| Pressure head at inlet   | 1.5 times filled height |

Table 2. Design Inputs

2.1.1. Design for tensile stress by Liu, Goh, and Silvester method:
Using method proposed by Liu, Goh, and Silvester as per Pilarczyk (2000), tensile strength requirement of the fabric is 34 kN/m. The cumulative factor of safety after considering installation damage, biological and chemical degradation, creep and seam strength is 3.9. Hence, the safe tensile capacity required is 133 kN/m.

2.1.2. Design for tensile stress by Timoshenko method
Design based on the method proposed by Timoshenko as per Bezuijen and Vastenburg (2013) for a height of filling of 2.5 m after filling is 39 kN/m. Assuming an overall strength reduction factor of 3.5, the design tensile strength requirement will be 137 kN/m. A safety factor of 1.1 to 1.2 is normally used for geosynthetic tubes, so design tensile strength is 164 kN/m.

2.1.3. GeoCoPS
Geosynthetic Confined Pressurized Slurry (GeoCoPS) is an interactive program for the design of geosynthetic tubes based on Leshchinsky and Leshchinsky (1996). The geometry of the tube and the circumferential and longitudinal tensile strength required for the geosynthetic tube are estimated by the program. The computations account for reduction factors related to seam strength, durability, creep and installation damage. Results are obtained by solving a differential equation subjected to design constraints.

The analysis carried out using GeoCoPS shows that with the increase in fill ratio, slurry density or pumping pressure at inlet, the tensile strength requirement also increases. The tensile strength requirement for achieving a fill height of 2.5 m is 133 kN/m. The software result is given in Fig. 3. Factor of safety for seam strength and creep are varied and strength requirements are verified in the example calculations.
2.1.4. Requirement of Seam and material strengths based on results from various methods

From the above three methods, the required seam strength is 160 kN/m. The strength of seams made in the factory is approximately 50% to 80% of maximum strength of geosynthetic material (Bezuijen and Vastenburg (2013)). Assuming 80%, the strength of material required would be 200 kN/m.

2.2. Design of Apparent opening size ($O_{95}$)

It is the property of the geosynthetic material which indicates the diameter of the approximate largest particle that would effectively pass through a geotextile.

2.2.1. AASHTO Method (Pilarczyk(2000))

The criteria given by American Association of State Highway and Transport officials (AASHTO) is as below:

- Soil with less than 50% passing sieve No.200 (75 microns): $O_{95} < 0.59$ mm
- Soil with greater than 50% passing sieve No.200 (75 microns): $O_{95} < 0.3$ mm

Based on analysis of grab samples collected in the study area, $O_{95}$ shall be less than 0.59 mm.

2.2.2. Bezuijen and Vastenburg (2013) method

For dynamic load (wave attack), the required pore size ($O_{95}$) of the geosynthetic material shall satisfy the following criteria.
\[ O_{90} < 1.5 \times D_{10} \times C_u^2 \]  
\( (1) \)

\[ O_{90} \leq D_{90} \]  
\( (2) \)

Where \( C_u \) = Uniformity coefficient from Grain size distribution curve. 
\( D_{10} \) = Effective size of particle. 
\( D_{90} \) = Particle size such that 90% of particles are smaller than this size. 

Soil used for filling has the following properties.

\( D_{10} = 0.083 \text{mm} \)
\( D_{90} = 0.285 \text{mm} \)
\( C_u = 1.77 \)

As per the criteria (1) and (2), \( O_{90} \) should be less than 0.166 mm and less than or equal to 0.285 mm respectively.

As per Bezuijen and Vastenburg (2013), the above criterion is for high hydraulic load. Hence for moderate load, geosynthetic tubes with apparent opening size of 0.25 mm may be used.

2.3. UV Resistance

The geosynthetics under water and in the inter-tidal zone show very little degradation in strength in comparison with geosynthetics placed on land. In the inter-tidal zone, the geosynthetics are covered very soon by algae which provide very good UV protection. Hence, the material with 75% of its original strength after an exposure of 500 hours to UV radiation (tested as per ASTM D 4355 (2007)) is found to be sufficient in this case.

2.4. Type of geotextile tube fabric

Geotextile tubes are usually manufactured using polypropylene or polyester fabric. Polyester is prone to hydrolysis under wet conditions. At moderate temperature, a loss of strength of 5% is expected (Pilarczyk (2000)). For longer duration in dilute alkaline condition, performance of polyester is moderate while polypropylene is good as per Pilarczyk (2000). As a larger life period is expected for the structure, use of geosynthetic tubes made of polypropylene fabric has been proposed considering marine conditions.

3. Stability of Geosynthetic tube under wave action

Under wave action, failure of geotextile tube structures may occur due to
- Sliding
- Overturning
- Settlement and bearing capacity failure

Available methods for checking the stability of stacked geosynthetic tubes are provided in
- Pilarczyk (2000)
- Kriel (2012)
While methods to check the stability of single Geotextile tube are provided in
- Van Steeg and Vastenburg (2010)
- Oh and Shin (2006)

Fig. 4 shows cross section of final breakwater configuration. Top tube is likely to be unstable when subjected to sliding forces and overturning moments due to wave breaking. Friction between the top layer of geosynthetic tube and bottom layer is still a matter of assumption.

![Fig. 4. Cross section of submerged breakwater](image)

3.1. Pilarczyk method (2000)

The stability study has accounted for the influence of fill ratio, density of sand, wave height, tube dimensions etc. The top of the geosynthetic tube is assumed at still water level as per this method. In the present case, the tube is located 0.5 m below Chart Datum (CD). Hence wave loading would be lesser on the structure. The assumption in Pilarczyk method is that for longer wave periods the overflowing mass of water will cause a hydrostatic pressure distribution at the front of the top tube while atmospheric pressure will be acting on the lee side as shown in Fig. 5. The calculation of overturning and restoring moment showed that the top geosynthetic tube is safe with a factor of safety of 2.65.

![Fig. 5. Wave loading on the top geosynthetic tube after Pilarczyk (2000)](image)
3.2. Kriel (2012)

Goda method has been modified by multiplying wave reduction factor $\chi$ for wave force calculation. The stability of top geosynthetic tube against overturning and sliding were estimated and found to be safe with a factor of safety (FoS) of 3.78 and 18 respectively.

3.3. Bearing Capacity and settlement

The overburden pressure and gravity weight of structure as transmitted to the base soil has been checked against the ultimate bearing capacity of base soil. Wave load is assumed to act on a rectangular block having same height and weight as the submerged breakwater cross section. Brinch Hansen (1970) method is used to check the bearing capacity. As the soil profile shows the presence of only cohesionless soils, immediate settlement is expected. The structure is found to be safe for bearing capacity and settlement criteria with a FoS of 5.

3.4. Comparison of wave loading on the geosynthetic tube by Pilarczyk (2000) and Kriel (2012) methods

The horizontal force calculated based on Pilarczyk method is 114.4 kN per metre length of the tube while from modified Goda method as per Kriel (2012), it is 43.6 kN per metre length of the tube. Since there is a substantial variation between the values, the wave loads were estimated using the software package, IH2VOF developed by IH Cantabria. The maximum horizontal loading by the waves on the submerged breakwater as shown in Fig. 6 is found to be 45.55 kN per metre length of breakwater. Pilarczyk method is found to provide an over estimate of load.

![Fig. 6. (a) Irregular wave input, (b) Wave loading on the submerged breakwater based on IH2VOF](image)

4. Estimation of scour around the submerged breakwater

Scour depth near the structure is estimated using Lee & Mizutani (2008) (on seaward side) and Young & Testik (2009) (behind breakwater) methods. Both methods are based on laboratory test results, where the incident wave is allowed to act for 5000 and 3000 cycles for Lee & Mizutani (2008) and Young & Testik (2009) methods respectively before measuring the scour. For a 2 m wave, the maximum scour depths at the offshore and onshore side are 75 cm and 8 cm respectively. For a 3 m wave, the maximum scour depths at the offshore and onshore side are 1.1 m and 20 cm respectively. The results are for continuous regular wave action and may not represent the
Suitable scour protection shall be provided at the front of breakwater. The submerged breakwater shall be constantly monitored for scour after construction by carrying out monthly bathymetry surveys. Sand filled geosynthetic bags encased in polymer rope gabions shall be placed on the seaward / leeward sides for scour protection.

**5. Conclusion**

Geosynthetic tubes are increasingly being used for construction of coastal protection structures like breakwaters, groins, seawall, protection of beach fill etc. This study proposes to use geosynthetic tubes for construction of submerged breakwater for shore protection at Kadalur Periyakuppam, Tamil Nadu. The design tensile strength of the geosynthetic tubes has been determined such that it can withstand the stresses developed in circumferential and longitudinal directions during filling. The design tensile strength of the material is 200 kN/m. Material should have optimum apparent opening size to hold the soil particles as well as to allow the water to drain off easily. Based on the design, an apparent opening size of 0.25 mm is provided. The geosynthetic material is designed to have a tensile strength of 75% of actual strength after 500 hours exposure to UV radiation. Stability analysis of the breakwater is carried out using different methods available in the literature as there are no standard guidelines available for estimating the wave loading on the geosynthetic tubes. The wave loading estimated from available methods is 45 kN per metre length of breakwater. The breakwater is safe against Overturning (FoS = 2.65), Sliding (FoS = 18) and bearing capacity (FoS = 5). For a 2 m wave, maximum scour depths at the offshore and onshore side are 75 cm and 8 cm respectively.

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