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An Engineering Method For The Preliminary Functional Design Of Perched Beaches. Theoretical Approach

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ABSTRACT


Perched beaches are an attractive nourishment design alternative especially when either the site conditions or the characteristics of both the native and the borrow sands lead to a non-intersecting profile. The observation and suggestion of the use of this type of coastal defense scheme dates back to the 1960’s, as well as the international experience in its construction. However, in spite of its use and the field and laboratory studies performed to-date, no design engineering guidance is available to support its design. Key dimensionless parameters that will be able to explain the performance of perched beaches have been identified, linking basic design variables such as: the wave height and period, the crest width and height, the depth at the toe of the sill, and the sand settling velocity. An engineering 4-step conceptual design method has been anticipated. This work will be expanded by systematic mobile-bed physical model tests - to be performed in a 36 x 3 x 1.5 m wave flume -, with the goal of producing engineering preliminary functional design guidelines of perched beaches based on the key dimensionless parameters herein identified.

ADDITIONAL INDEX WORDS: Coastal defense, submerged sills, beach performance, dimensionless parameters.

INTRODUCTION

The concept of a "perched beach" is based in the observation - back in the 1960's - of a natural detached structure at the lower part of the profile at Algodones Beach (Gulf of California) as shown in Figure 1, suggesting a wider beach than the neighboring ones (Inman and Frautschy, 1966).

Figure 1. Algodones Beach cross-shore profile (Inman and Frautschy, 1966).

The underlying concept of a "perched beach" is the reduction of sand needs when dealing with the creation of a sandy beach by the construction of a submerged sill somewhere along the beach profile. Usually, the sill's crest elevation is designed below low tide elevation as an attempt to restrict the cross-shore transport during storms, thus reducing the seaward depth limit of the beach profile (Figure 2). The two most typical situations where this situation is produced are: (1) when dealing with non-intersecting profiles between borrow sand profile and natural profile (Dean, 1991) as shown in Figure 3, and (2) when the seabed slope is relatively high such as in volanic islands or rocky seabeds, as shown in Figure 4.

Figure 2. Typical engineered perched beach.
A literature review has shown a mixture of successes and failures in the application of this concept of beach protection. Since most works are site-specific, not an adequate discussion of results has been performed and therefore there is a lack of lessons learned and of understanding of the mechanisms that lead to success or failure when applying the "perched beach" concept. However, in spite of its use and the field and laboratory studies performed to-date, no design engineering guidance is available to support its design.

Figure 3. Non-intersecting profile such as when using borrow sand finer than the native sand.

Figure 4. Non-intersecting profile such as when engineering a beach on a relatively steep seabed.

On a scenario of increasing demand of sand for beach nourishment purposes as well as of increasing demand for recreational beaches, it becomes necessary to provide the design engineers with guidance on the use of perched beaches. This paper deals with the theoretical approach to the production of such engineering guidelines for the use of perched beaches as a recreational beach creation tool as well as a coastal protection scheme alternative assuming the validity of the linear wave theory.

METHODS

The Buckingham Pi Theorem is judged to be appropriate to deal with the purpose of this paper and help understand the dimensional parameters that may control the response of a perched beach when attacked by a certain wave climate (Buckingham, 1914). The theorem states that given $n$ dimensional variables that are physically relevant in a given problem - in this particular case, the success (or failure) of a perched beach construction against a certain wave climate - that are inter-related by an (unknown) dimensionally homogeneous set of equations, these can be expressed via a functional relationship of the form:

$$F(q_1, q_2, ..., q_n) = 0$$

Where $q_i$ are the relevant variables of the problem.

Definition of Relevant Variables

First, the relevant variables of this problem are defined (Figure 5). The variables may be grouped into three types:

- Wave climate variables: Wave height at the toe of the structure, $H_{toe}$ (m); Wave period, $T$ (s).
- Location of the submerged sill: Depth at the toe of the structure along the profile, $h_{toe}$ (m).
- Sill geometry: Sill height, $h_s$ (m); Sill crest width, $B$ (m).

An useful variable is the freeboard, $R$ (m), which may be derived from the difference between the depth at the toe of the structure ($h_{toe}$) and the sill height ($h_s$).

![Figure 5. Definition sketch of problem variables.](image)

Identification of Dimensionless Parameters

Once the relevant variables have been selected, a set of dimensionless parameters has to be derived. This way, the Buckingham Pi Theorem may be expressed in a much more compact form:

$$\Phi(\pi_1, \pi_2, ..., \pi_{n-k}) = 0$$

Assuming the validity of the linear wave theory, and under 2D circumstances, there is a relationship between the deepwater wave height, $H_0$ (m) and the wave height at the toe of the structure $H_{toe}$ (m) for a given wave period ($T$). Also, since the deepwater wave length $L_0$ (m) is a function of the wave period ($T$), the deepwater wave steepness is considered as the first dimensionless parameter - a classical indicator of wave aggressiveness:

$$\pi_1 = \frac{H_0}{T^2}$$

The "plunger parameter" has been considered as defined by Sumer et al. (2005), and is the second dimensionless parameter. It is defined as

$$\pi_2 = \frac{T}{\sqrt{g \frac{H_{toe}}{h_{toe}}}}$$

Where $g$ (m s$^{-2}$) is the acceleration due to gravity. The third dimensionless parameter is the dimensional sill crest
width defined as - thus relating the structure and the wave climate:

\[ \pi_3 = \frac{B}{H_0} \]

The fourth dimensionless parameter has to do with the degree of protection provided by the sill against wave action, measured as:

\[ \pi_4 = \frac{h_c}{h_{toe} + H_{toe}} \]

Finally, information is needed concerning the characterization of the borrow sand. For that purpose, the well-known Dean’s parameter (Dean, 1973) becomes useful. Therefore, the fifth dimensionless parameter is written as:

\[ \pi_5 = \frac{H_0}{\omega \omega} \]

Where \( \omega \) (m s\(^{-1}\)) is the settling velocity of the borrow sand. All \( \pi \)-groups defined above are independent.

**Theoretical Relationships Between Dimensionless Pi Groups**

It is anticipated that success / failure domains may be identified and described in terms of pairs of \( \pi \)-groups. The different possible system response may be studied from definition of success / failure regions defined on \( \pi_i - \pi_j \) cartesian coordinates as schematized on Figure 6, 7, and 8.

Figure 6 depicts possible success / failure relationships between two \( \pi \)-groups described as an ascending relationship. In this particular case, functional relationships to delimitate the success / failure domain may be obtained in the following shape:

\[ \pi_j = a_{ij} + m_{ij} \pi_i \]

Where \( a_{ij} \) and \( m_{ij} \) are the parameters defining the straight lines as y-axis coordinate at origin and slope.

The success domain may be bounded between two potential relationships as described above (left), or the failure domain may be bounded between two potential relationships as described above (right) - and therefore the success domain is unbounded.

Figure 7 depicts possible success / failure relationships between two \( \pi \)-groups described as a descending relationship. In this particular case, functional relationships to delimitate the success / failure domain may be obtained in the following shape:

\[ \pi_i + m_{ij} \pi_j = k_{ij} \]

Where \( m_{ij} \) and \( k_{ij} \) are the parameters defining the straight lines.

The success domain may be bounded between two potential relationships as described above (left), or the failure domain may be bounded between two potential relationships as described above (right) - and therefore the success domain is unbounded.

Figure 8 depicts possible success / failure relationships between two \( \pi \)-groups described as a region. In this particular case, functional relationships to delimitate the success / failure domain may be obtained in the following shape:

\[ (\pi_i, \pi_j) \in R \]

Where \( R \) symbolizes the success / failure region.

**ANTICIPATED DESIGN GUIDANCE**

An engineering 4-step conceptual design method has been anticipated and is proposed herein. First, it is assumed that the success / failure domains for the behavior of a perched beach do exist in any of the three possible relationships shown in Figure 6, Figure 7 and Figure 8.
One possible rational behind the design guidance will be the following:

1) Estimate the characteristic wave climate of the study area, and select the design deepwater wave height, \( H_0 \) (m), and the wave period, \( T \) (s), and get \( \pi_i \).

2) Decide on the location (depth) of the submerged sill defined by the depth at the toe of the structure, \( h_{sa} \) (m). Once this is done, the wave height at the toe of the structure \( H_{1\text{e}} \) (m) may be obtained by using, for instance, linear wave theory. \( \pi_i \) may be then computed.

3) Decide on the width of the submerged sill \( B \) (m). Once this is done, the dimensionless width \( \pi_i \) may be immediately obtained.

4) Decide on the submerged sill height \( h_s \) (m). Once this is done, the dimensionless parameter \( \pi_i \) may be computed.

5) Decide on the borrow sand to be used to carry out the beach nourishment, and consider its settling velocity \( \omega \) (m s\(^{-1}\)) and compute \( \pi_i \).

It is foreseen that the decision making process as described above may lead to an iterative procedure until a combination of design parameters are found to comply with the success domains for the \( \pi_i \) combinations where success / failure domains may be obtained. Understanding of the relationships between all five \( \pi \)-groups as defined, and especially as for what concerns the location and shape of the success / failure domains as represented in the \( \pi_i \) - \( \pi_j \) planes will allow for the set up of a design guidance methodology as described.

**FURTHER EXPERIMENTAL WORK**

In order to be able to find the success / failure domains for the behavior of perched beaches, two-dimensional reduced scale laboratory tests will be performed. This work will be expanded by systematic mobile-bed physical model tests - to be performed in a 36 x 3 x 1.5 m wave flume - , with the goal of producing numerical results. This work will be expanded by systematic laboratory tests that are expected to allow the formulation of a design process as described in this paper.

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