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

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ABSTRACT

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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 volcanic islands or rocky seabeds, as shown in Figure 4.

Since that time, several beaches have been engineered following the perched beach concept (Sivard, 1971; Douglass and Weggel, 1987; Ferrante, Franco, and Boer, 1992; Lamberti and Mancinelli, 1996; Dean, Chen, and Browder, 1997; Stauble and Tagar, 2003; Faraci, Scandura, and Foti, 2014). Also, laboratory tests have been performed by using mobile-bed models (Chatham, 1972; Sorensen and Beil, 1988; Chiaia, Damiani, and Petrillo, 1992; Groenewoud *et al.*, 1996; CEDEX, 2000; Moreno, 2003; Lorenzoni *et al.*, 2009, 2012).

A common fact in the preceding work is that they have been developed under case study site-specific conditions, or the beach surveys have not been as detailed as desirable, or the laboratory tests have either not been systematic or to a scale where the scale effects have not been minimize to impact the involved processes (Le Méhauté, 1976; Hughes, 1993).

Figure 2. Typical engineered perched beach.

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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 to 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 - and that are inter-

related by an (unknown) dimensionally homogeneous set of equations, these can be expressed via a functional relationship of the form:

$$F(q_1, q_2, \dots, q_n) = 0$$

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_c (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_c).

Figure 5. Definition sketch of problem variables.

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:

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

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:

$$\pi_1 = \frac{H_0}{L_0}$$

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

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

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:

$$\pi_5 = \frac{H_0}{\omega T}$$

Where ω (m s^{-1}) is the settling velocity of the borrow sand. All π -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 π -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 π -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.

Figure 6. Possible success / failure relationships between two π -groups (ascending relationship). Success domain: bounded (left) or unbounded (right).

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 π -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.

Figure 7. Possible success / failure relationships between two π -groups (descending relationship). Success domain: bounded (left) or unbounded (right).

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 π -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.

Figure 8. Possible success / failure relationships between two π -groups (regional relationship). Success domain: bounded (left) or unbounded (right).

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.

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 rationale 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 π_1 .
- 2) Decide on the location (depth) of the submerged sill defined by the depth at the toe of the structure, h_{toe} (m). Once this is done, the wave height at the toe of the structure H_{toe} (m) may be obtained by using, for instance, linear wave theory. π_2 may be then computed.
- 3) Decide on the width of the submerged sill B (m). Once this is done, the dimensionless crest width π_3 may be immediately obtained.
- 4) Decide on the submerged sill height h_c (m). Once this is done, the dimensionless parameter π_4 may be computed.
- 5) Decide on the borrow sand to be used to carry out the beach nourishment, and consider its settling velocity ω (m s^{-1}) and compute π_5 .

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 $\pi_i - \pi_j$ combinations where success / failure domains may be obtained. Understanding of the relationships between all five π -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 success / failure domains that may be analyzed under the perspective of the π -groups identified and discussed above.

Providing the success / failure domains are identified, engineering preliminary functional design guidelines of perched beaches will be based on the π -groups (and ultimately on the key design parameters herein identified).

The mobile-bed beach profile evolution will be followed-up with great detail so as to assess when profile equilibrium against wave action is reached.

Ideally, a set of erosive wave conditions will be tested in combination with different submerged structures. The stability of the submerged structure will not be considered, since there has been extensive work already done elsewhere (DELOS, 2004).

CONCLUSIONS

Although the perched beach concept was suggested several decades ago, and in spite of the number of engineered beaches using this coastal defense scheme worldwide, there is no clear understanding of the success and failure response.

Theoretical analysis, field work, and laboratory experiments have been used with an aim to provide an understanding of the working mechanisms that control the beach response.

The present work sets up a framework for the analysis of the

perched beach response based on dimensional analysis, where a design guidance is anticipated.

The design guidance is based on five dimensionless parameters that are constructed with the basic engineering variables needed to design a perched beach. An iterative process is also anticipated to find a combination of parameters that satisfies the designer and the boundary conditions of his / her problem in order to achieve the success domain, that is the desired behavior of the coastal defense scheme so as to improve natural conditions (i.e. without any perched beach).

In order to identify the success / failure domains, a set of systematic laboratory tests will be performed that are expected to allow the formulation of a design process as described in this paper.

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