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Sand-filled geosystems in river and coastal engineering based on case study applications

Application des géo-conteneurs remplis de sable dans les domaines du genie côtier et fluvial

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ABSTRACT: The interest in using sand-filled geosystems in hydraulic engineering is gradually increasing. However, generally accepted guidelines for designing are yet to be made available/set up and a significant part of the knowledge still stems from the practical experiences worldwide. Most of the design rules applied to sand-filled geosystems are empirical in nature and this means that prior experience is therefore required.

Two case studies of the application of sand-filled geosystems, in which the authors were involved, are discussed in this paper. The case studies concern the design of an artificial perched beach private of a residential building in the Middle East, and the design review of the studies to recover the navigability of a river in Latin America.

RÉSUMÉ: L‘utilisation de géo-systèmes ou géo-conteneurs remplis de sable dans le génie hydraulique resprésente un intérêt grandissant. Cependant, des directives généralement admises pour la conception doivent encore être mises à disposition/mises en place. Une partie significante des connaissances de ce sujet provient encore des expérience pratiques réalisées dans le monde entier. La plupart des règles de conception appliquées aux géo-systèmes remplis de sable sont de nature empirique, ce qui signifie que l‘expérience est par conséquent nécessaire. Cet article présente deux études de cas sur l‘application de géo-systèmes remlis de sable, auxquelle les auteurs ont participé. Les études de cas portent sur la conception d‘une plage artificielle perchée appartenant à un bâtiment résidentiel du Moyen-Orient et sur la révision des études de conception visant à rétablir la navigation sur une rivière en Amérique Latine.

Keywords: Geosystems; navigable channel; maintenance dredging; environmental impact.

1 INTRODUCTION

Sand-filled geosystems are used more and more in hydraulic engineering. However, the design of these sand-filled geosystems is in general still based on experience from other projects, and there are not yet generally accepted international guidelines for the design of these structures. Most of the design rules applied on sand-filled geosystems (Bezuijen et Vastenburg, 2013 ; das Neves, 2011 ; das Neves et al., 2015), are empirical in nature, which shows the importance on feedback and experience in the use of sand-filled geosystems in hydraulic engineering projects worldwide.

Two case studies of the application of sand-filled geosystems, in which the authors were involved, are discussed in this paper. The case studies concern the design of an artificial perched beach private of a residential building in the Middle

East, and the design review of the studies to recover the navigability of a river in Latin America.

In the first project, the sole purpose of the artificial beach was recreation. Main constraints on design were imposed by the architectural design, namely an overall new orientation of the coastline, and the presence of a navigation channel within a limited distance, of which the function should be preserved. Within the constraints imposed, a submerged sill consisting of sand-filled geosystems is designed to intercept the nourished beach profile at a certain distance and depth, supporting the toe of the artificial sand beach. The various stages of the design processes included the definition of the functional requirements of the structure and the geometrical design of the sand-filled geosystem elements (filling heights, stacking, lengths…), the hydraulic and geotechnical design, and the definition of minimum property requirements for the materials. The overall requirements for the geosystem elements are as follows: be sufficiently permeable; be sufficiently sand-tight; be resistant to pressures during filling; be resistant to localised loads (tearing, vandalism, etc.); and be resistant to UV radiation. A minimum tensile strength of the geotextile is required to withstand the installation conditions. It is as well anticipated that the geosystem will require additional monitoring, to ensure that eventual damage to the geosystem does not result in losses of beach and filling material. It was further recommended that each of the sand-filled geosystem elements has a different length to allow the junctions between elements to be offset and the use of elements with flat-finish termination for more appropriate junction with adjacent element. The placing and filling of the sand-filled geosystems can be achieved in a number of ways e.g. plant operated from land or from a floating platform/barge. The plant will require the use of e.g. pumps, floating pipelines, and a container to make the mixtures of water and sand. An experienced team on site is crucial to ensure that the material is properly installed. Since damage to the geosystem often occurs due to poor installation practice and handling, an experienced manufacturer/contractor on site is an absolute requirement. It should be added that although, at this specific location, the placement of sand-filled geosystem elements is expectedly more expensive than the placement of a gravel layer for instance, essentially due to material and construction related costs, this was the preferred option by the Client.

For the second project, the authors were involved in the design review of the studies to recover the navigability of a river, including dredging and the construction of river training works, for which sand-filled geosystems (in the form of tubes, bags and mattresses) are being considered. The functional requirements for this project concern the maintenance of a navigable channel during low water periods, by means of dredging and/or structures incorporating sand-filled geosystems as flow guiding structures, bank protection and closure of secondary channels. Some important aspects, including scour development and its impact on the geosystems' deformation and the loss of structure functionality and even failure due to excessive deformation and/or fabric tearing, and its vulnerability to deformations caused by internal sand movement, are investigated.

2 ARTIFICIAL BEACH FOR A RESIDENTIAL BUIDLING (MIDDLE EAST)

The design lifetime of the project is 25 years. The project comprises the design and construction of a building and landscape, slightly rotated with respect to the existing alignment and of the marine infrastructure. The marine infrastructure consists of the following structures along the residential building frontage:

* Beach nourishment with sand along the whole frontage;

* A submerged sand-filled geosystem to retain the artificial beach toe;

* Removal of the existing breakwater – to be removed as the new beach is to be partially constructed on top of it; and

* Two new edge walls along the promenades and the beach of the residential building.

2.1 Hydrodynamic design conditions

The hydrodynamic exposure conditions at the residential building are corresponding to shelter conditions, main drivers are the changes in water level due to tides and to future predicted sea level rise. Ship-induced waves are also considered in the design.

2.2 Beach and retaining structure design

The design shoreline assumes a spline shape, as per architectural and structural design of the residential building. A spline is a curve defined by two or more points of control.

A median grain size diameter of 300 µm, corresponding to a fine sand, is adopted in the design.

Dean's equilibrium profile (USACE, 2002) is considered in the beach design profile, as a first approach. Equilibirum beach profiles respond to wave forces by adjusting their form to a constant shape attributable to incident wave and/or sediment characteristics. Dean's equilibrium profile assumes that the profile shape depends only on the sediment size, and that incident waves govern the position of the shoreline.

Defining the beach design profile shape to an equilibrium profile concept has the anticipated benefit that lower modifications to that profile are expected after construction. However, the gentle slope assumed by the profile of Dean made the compatibility between existing and proposed elevations impractical to achieve, given the limited space available to confine that profile before reaching the navigation channel that exists at some distance from the residential building frontage.

The assessment carried out on the nourishment volume requirements and the loss of functions (i.e. navigation) resulted in the proposal of a beach design based on a perched beach concept, i.e. intersecting the beach slope at a certain point seaward with a retaining structure.

Beach retaining structures are also necessary at the north and south edges. The profile shape of Dean is used to predict the top crest level of the submerged beach toe retaining structure at the edge of the navigation channel. The design of the north and south edge retaining structures is based on concrete walls and is not included in this paper. Only the design of the beach toe retaining structure is included.

2.3 Beach toe retaining structure options

In an early stage of design it was considered to use (where possible) the existing breakwater structure as retaining structure. Although, this would be the most cost-effective solution because a lower volume of sand would be required to construct the beach, and because the existing breakwater would only have to be partly demolished, it was initially rejected. In summary the main issues raised there were:

* the residential building infrastructures and the existing breakwater are at a relatively short distance of each other, and for that reason the available beach width would be limited in a substantial part of the new beach;

* the reach of the existing breakwater is beyond the south edge wall, thus a new retaining structure with a length of approximately 50 m would have to be built; further the spline shoreline shape is in its most seaward position at this location making the compatibility between elevations difficult to achieve; also, more complex hydrodynamics are anticipated when transitions are present; and

* the existing breakwater would have to be partly demolished to different elevations and be prepared to avoid any hazards for all beach users.

Three options for the beach retaining toe retaining structure have since been considered during the pre-design phase, namely a gravel layer, sheet-piling and sand-filled geosystems. Of those three considered options, the gravel layer and the sand-filled geosystem options were the preferred alternatives to take forward. The valuation was based on costs, regional know-how and potential hazards posed to the beach user. Both the gravel and the geosystem offered equal potential to retain the beach. However, it is anticipated that the geosystem will require additional monitoring, to ensure that eventual damage to the geosystem does not result in losses of beach and filling material. The placement of sand-filled geosystem elements is expectedly more expensive than the placement of a gravel layer, essentially due to material and construction related costs.

In the following, new alternatives based on either a gravel layer or sand-filled geosystems beach toe retaining structures were developed. In consultation with the Client the preferred option was the one using sand-filled geosystems, from which new alternatives based on different beach slopes have been developed.

2.4 Sand-filled geosystem – hydraulic design

Based on the functional requirements and the local conditions (specifically the hydraulic and geotechnical conditions), the key dimensions of the overall beach retaining structure were established, most notable the characteristic cross-section, longitudinal profile, crest-height and slope.

The size (weight and dimensions) of the geotextile-encapsulated sand elements and their number were determined using applications and practical examples given in literature (Bezuijen et Vastenburg, 2013)

For the current project, the chosen theoretical diameter of the geosystem is 3.25 m in size, which is defined mostly on the geometrical design than on hydrodynamic conditions, which are as mentioned limited because of the shelter conditions at the project site. The fact that the retaining beach structure is built as a multi-layered stacking structure does not bring about any additional stability to the structure in general, and to the elements in the bottom layer in particular, as it is expected that without structural connections two tubes have no greater stability than one tube (Bezuijen et Vastenburg, 2013).

2.5 Sand-filled geosystem – geotechnical design

The geotechnical stability analysis is carried out with the software SLOPE/W 2007 (SLOPE/W, 2007), based on the Morgenstern-Price theory of failing through sliding.

There are many different ways of describing the strength of geotechnical materials in a slope stability analysis. Mohr-Coulomb criteria are applied as this is the most common way of describing the shear strength of geotechnical materials (soil and rock).

With SLOPE/W 2007 the safety factor for the stability of slopes is calculated. The calculated safety factors are compared with the recommended safety factor of 1.5 for long-term stability of slopes, as suggested by the U.S. Army Corps of Engineers (USACE, 2003), and many other agencies. For short-term stability a safety factor of 1.3 is acceptable.

The most critical alternative layout of the residential building beach in slope stability was chosen for this analysis. Among all the cross sections, the cross section on Figure 1 seems to be more critical in slope stability analysis because the seaward bottom edge of the geosystem is located exactly on the top edge of the navigational channel slope. In all the other cross sections at the seaside of the geosystem a horizontal berm exists. The mentioned cross section has the lowest stability factor of safety.

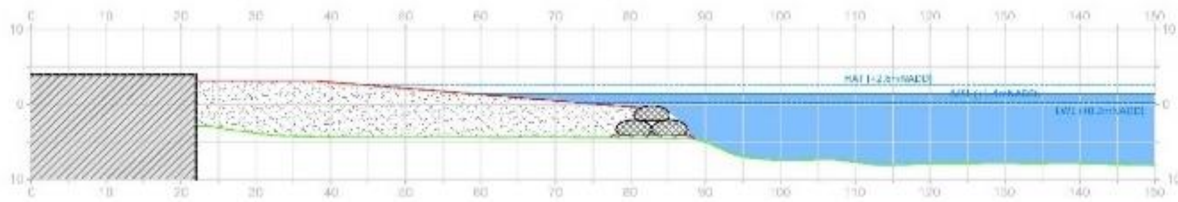

Figure 1: The critical cross sections of the residential building beach

Based on the geotechnical investigation and measurement campaign, the soil structure of the area south of the residential building beach consists of two layers. The top layer of the foundation is silty and clayey sand. The thickness of top layer is limited. However, to be conservative, 2 m thickness is considered for the silty and clayey sand layer.

The foundation bottom layer consists of medium to dense sand. In this layer high numbers (N-value) of standard penetration test (SPT) are registered.

For the slope stability analysis the lowest and the highest water levels are considered. The analysis and the presented results are based on the static condition. Seismic calculations have not been taken into account. It is observed that the variation of the water level from lowest to highest level has a negligible effect on the stability of the beach and the geosystem.

For both highest and lowest water level, the factor of safety of slope stability is higher than the requirements for long term conditons.

2.6 Execution methodology

Pre-fabricated geosystems are delivered to site with only a number of inlet/outlet openings required for the filling. Each of the sand-filled geosystem elements has a different length, to allow the junctions between elements to be offset. The installation of the geosystem, accompanied on site by an experienced team, consists of the two phases: laying out the geosystem, and pumping it up (filling). During the laying out, the geosystem made of Polypropylene (specific gravity lower than water) is carefully and completely unrolled and unfolded into the correct position in floatation, and is temporarily secured for the filling. The filling of the geosystem is accomplished by hydraulically pumping a mixture of sand and water into the system.

2.7 Periodic inspections and maintenance

Beach levels and shoreline design shape should be periodically inspected. Emergency or routine renourishment may be required to ensure the desired performance of the project. Furthermore, the following maintenance works can be expected (non-exhaustive list): mechanical redistribution of sand within the project area, grading, cleaning, and periodical removal of debris from the project area. Performance and condition monitoring are needed throughout the economic life of the project.

Damage to the geosystem could be due to a number of reasons – boat collisions/fishing gear, storm events, vandalism, damage during installation, failure of the geotextile material or natural wear and tear.... It is suggested that diver inspections are carried out annually for the first 10 years to assess the overall structural integrity and conditions of the sand-filled geosystems. The time between inspections could be extended to 3 years for the remainder of the 25 year estimated design lifetime.

3 RIVER TRAINING WORKS IN LATIN AMERICA

One of the longest rivers in Latin America, which is in the top 10 worldwide regarding sediment transport, is subject of this investigation. In the past, the river was used for transport of goods.

However, nowadays this transport is mainly performed on land, which has resulted in a loss of activity for river and marine transport. To restore and maintain navigabilty over 908 km of navigable channel, the governmental river manager awarded a 14-year lasting concession to the Contractor. Navigability is improved and maintained by dredging and river training works.

These river training works consist of different structures, namely (submerges) flow guiding structures, bank protection and closure of secondary channels. The flow guiding structures will guide the flow into the navigable channel at low water levels. The bank protection reduces the risk on bank instability, especially in narrow locations of the river. Closure structures for the secondary channels guide the water during low water events towards the main channel, resulting in an increase of the water level in the main channel and navigable channel.

Due to the lack of rock quarries in the proximity of the project zones and the enormous (expected) amount of dredged material caused by the enormous sediment load, the use of sand-filled geosystem elements are being considered for the construction of these river training works. The authors offered technical assistance to the Contractor during engineering phase, including the review of the design of the river training works in an approximately 270 km long river stretch, and the assessment of geotextile manufacturers.

The first step is the review of the functional design. In a second step of the review, the structural design process is reviewed, since this is of utmost importance to guaranty the structures' stability to the hydrodynamic forces. The stability of the structures depends on the design of the sand-filled geosystem elements themselves, as on the characteristics of the used geotextile as on the scour protection measures. Due to the impact of scour development on the geosystems' deformation, a structure might loose its functionality or even result in structural failure or fabric tearing.

3.1 *Functional design*

The functional design of the river training works is reviewed by the authors. The authors have developed a design methodology for flow guiding structures and closure structures in braided rivers. The main purpose of the developed design methodology is to minimize the amount of maintenance dredging works after construction of the river training structures. The review of the functional design of the river training works, based on this methodology, has resulted in the removal, adding and adaptation of structures, compared to the designer's design.

Based on a low water event, which is the design event to improve navigability on the river, the length of the flow guiding and closure structures is determined. Based on a high water design event, which determines the morphological evolution of the river bed, the methodology results in a crest level, which minimizes the amount of dredging works in the main channel. The length and crest level of these structures are the base of the structural design.

3.2 *Structural design*

The use of sand-filled geosystems in river training works has some advantages compared to classical solutions, like rocks or gabions. Since (a part of) the dredged material can be used as filling material of the geosystems, the environmental impact of the dredging works will be reduced significantly. Additionally, the use of sand-filled geosystems has the advantage that they have a limited and non-permanent impact on the natural processes in the river. For these reasons and due to a lack of rock quarries in the proximity of the project area, the use of sand-filled geosystems is strongly advised.

3.3 *River training works*

The design of the river training structures can be divided into two parts. On one hand, the actual river training structures can be considered, on the other hand dredging works. The design of the river training structures – mostly performed in the form of tubes – depends on several parameters. As a first important parameter, the hydrodynamic forces in the river are taken into consideration. Based on hydraulic modelling of the river, performed by both the designer of the river training structures and the authors, it can be concluded that very high flow velocities (up to 3 m/s and higher) occur in the studied part of the river. Not all types of sand-filled geosystems are capable of coping with these flow velocities. For example, sand-filled geosystems in the form of bags are useless at flow velocities of 2.5 m/s or more, since the filled material in the bags will internally start moving, resulting in deformations, which might affect the structure's functionality and possibly even result in failure.

Stability calculations are based on assumed values of different parameters. For example, the design of sand-filled geosystems is strongly dependent on the porosity of the geosystem. For the same dimensions of geosystem, a geosystem with higher porosity might become unstable, where the geosystem with lower porosity remains stable. Therefore, the authors recommended a thorough sensitivity analysis of all the different assumed parameters for the stability calculations.

The designer of sand-filled geosystems should take into account that these geosystems are intrinsically more vulnerable than rock protection or gabions, and therefore require regular maintenance. The geosystems might be protected mechanically against vandalism or debris. These mechanical protections might be performed by other geosystems, in the form of aprons, mattresses or bags. On one hand, the use of mattresses and bags is discouraged, both due to the high flow velocities as due to the fact that these geosystems are not able to be in full contact with the tube due to its form. On the other hand, geotextile aprons are difficult to fix to the sand-filled geosystem. The best fixation is performed by wrapping the apron around the tubes. Other more complex fixation solutions like gramps are less reliable under solid transport (both sediment and debris).

Since all possible above mentioned mechanical protective measures have disadvantages, the authors suggested the designer to use a stronger fabric for the construction of the tubes, possibly the same fabric as would be used for aprons. The disadvantage of this fabric is that it is limited to 500 g/m², where the proposed fabric of the design is limited to 1000 g/m². Therefore, the authors suggested the designer to prepare a detailed monitoring and maintenance plan during the life cycle of the tubes.

As indicated earlier, the design of sand-filled geosystems is empirically based. Therefore, the authors suggested to perform an experiment with a complete prototype of a sand-filled geosystem in a critical stretch of the river. Observation of this prototype could possibly lead to an improvement of the design and to an optimization of the costs.

3.4 Scour protection

Due to the implementation of the river training structures, the flow patterns in the river change. This change in flow patterns might result in excessive scour around the structures, which can threaten the overall structural stability and functionality of the river training structures. The estimation of the scour depth and scour evolution is still a difficult topic for academics and professionals. Therefore, a sensitivity analysis of different scour formulae and the different used parameters is recommended by the authors. Due to the lack of rock quarries in the proximity of the project area, the use of geotextiles is considered for the design of the scour protection.

Two different uses of geosystems are investigated by the authors. As a first option, the use of sacrificial sand-filled geosystems (geobags) is investigated. These bags fall into the scour pit and protect the pit in this way from further excessive scouring. As a second option, the use of an anti-scour apron in geotextile is investigated. At the end of this geotextile, a sand-filled geosystem (in the form of a tube or a bag) is connected. If scour occurs at the end of the scour protection, the geosystem falls into the scour pit, protecting it against excessive scouring. The zone between the river training structure and geosystem, connected to the anti-scour apron, is still protected by the apron.

The scour protection measures have to be installed at critical zones in the beginning of the construction works of the river training structure. However, due to the uncertainty of the scour depth and scour evolution estimations, the authors proposed to perform a detailed monitoring and maintenance plan for the scour protection. Different monitoring methods were proposed by the authors, as there are sonar, magnetic sliding collars and float-out devices. In the end, the use of sonar was recommended, because this gives a continuous indication of the bed evolution.

In case the monitoring of the structures reveals scour problems at the structures, the most suitable solution needs to be selected to prevent excessive scour, which can endanger the functionality of the river training structure. The experience of the designer and the contractor are therefore necessary.

4 CONCLUSIONS

For the residential building beach, the theoretical diameter of the geosystem 3.25 m is considered. The most critical cross section of the beach (combination of the sand beach and the geosystem on the seabed) is considered for slope stability analysis. A slope stability safety factor higher than requirement has been achieved. Beach levels and shoreline design shape should be periodically inspected and it is possible that the emergency or routine renourishments are required to ensure the desired performance.

For the study on the Latin American river, the main purpose of the developed design methodology is minimizing the amount of maintenance dredging works after construction of the river training structures. As a part of the dredged material can be used as filling material of the geosystems, the environmental impact of the dredging works will be reduced significantly by using sand-filled geosystems. These geosystems might need to be protected mechanically against vandalism or debris.

For the construction phase, it is also recommended that each of the sand-filled geosystem elements have different lengths, to allow the junctions between elements to be offset.

As the amount of required works is very substantial, a comprehensive monitoring programme is recommended, which could give feedback for the design of the works, scour protective measures and mechanical protections for the geosystems. This means phasing some of the interventions, implementing pilot zones and feedback the lessons learnt to other zones.

5 REFERENCES

Bezuijen, A., Vastenburg, E.W., 2013. Geosystems – Design Rules and Applications, CRC Press, Taylor & Francis Group.

das Neves, L., 2011. Experimental Stability Analysis of Geotextile Encapsulated-sand Systems Under Wave-loading, PhD Thesis University of Porto, Faculty of Engineering, Portugal.

das Neves, L., Moreira, A., Taveira-Pinto, F., Lopes, M.L., Veloso-Gomes, F., 2015. Performance of submerged nearshore sand-filled geosystems for coastal protection, Coastal Engineering, Volume 95, Pages 147-159.

USACE, 2002. EM 1110-2-1100, Coastal Engineering Manual, USACE.

SLOPE/W, 2007. Stability modeling with SLOPE/W 2007, an engineering methodology, GEO-SLOPE International Ltd.

USACE, 2003. Engineering and design, Slope Stability, EM 1110-2-1902, USACE.