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A simplified algorithm for conceptual estimation of the material quantities of rubble-mound breakwaters

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Abstract. A simplified algorithm is proposed for fast estimation of the material quantities required for the construction of rubble-mound breakwaters. The proposed algorithm is able to employ only the data available at feasibility study phase such as the maximum draught of the design ship selected to transport the cargos to the harbor despite, because at the feasibility phase, information for the planned harbor is likely to be very limited. A linear-constant waterdepth model together with a proposed section configuration for the breakwaters, which is customary for harbors, is considered to calculate the quantity of materials. The numerical simulation of the wave characteristics has been verified using the recorded wave data collected by a buoy installed near the Neka harbor in Caspian Sea waters. A case study has been also applied to four harbors to validate the proposed algorithm. The estimated weights using the proposed linear-constant and multi-linear waterdepth models were compared using the bathymetry maps and layouts of these harbors. A computer program, written in QBasic language, has been developed to simulate the wave characteristics and to estimate the material quantities needed to construct a rubble-mound breakwater. The obtained results show that taking into account the acceptable accuracies normally applied to the feasibility study and conceptual design phases, the proposed algorithm is sufficiently accurate and highly effective for the conceptual estimation of materials' quantities of breakwaters in the feasibility study phase of harbor projects.

Keywords: rubble-mound; breakwater; analytical model; material quantity; conceptual estimate

1. Introduction

Breakwaters are important parts of a large number of harbors worldwide and their contribution to the construction cost of harbors is significant. Considering the fact that the harbors, have a big impact on the economic level and industrial progress of a country, and are vital for the import and export of goods, it shows the weighty role of breakwaters.

For preliminary planning and conceptual design purposes, the allocation of budget and obtaining necessary approvals, it is of great help to be able to estimate roughly the quantity of the bulk materials required for the construction of breakwaters. Rubble-mound breakwaters are the most commonly constructed type of breakwaters. Major parameters affecting the design of breakwaters are hydrodynamic wave actions, the unit weight of armor units and seawater, the geometrical shape

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of armor units and breakwaters, as well as the seabed soil properties. In the calculation and analysis of the wave parameters in the seas and oceans, the Bretschneider, JONSWAP and Pierson-Moskowitz spectrums and formulas are typically employed (Sadeghi (2008), US Army Corps of Engineers (2012)). Stream Function, Solitary and Cnoidal wave theories are used mainly for the evaluation of waves in shallow waters. Airy, Stocks'' second and fifth orders, and Trochoidal waves are used to determine the wave characteristics in deep waters (Sadeghi 2001, Sadeghi 2007).

Many different investigations have been performed on breakwaters considering different parameters. Among them, Van Gent (2003) overviewed the developments in the conceptual design of rubble mound breakwaters. Their overview was concerned the design aspects related to the stability of armor layers, feasibility of a single layer of Cube armors, the influence of shallow foreshores on the stability of rock slopes, and the stability of near-bed structures. This overview provides a guide to the conceptual design of rubble mound breakwaters. Zhao *et al*. (2013) presented a three-dimensional integrated numerical model where the wave-induced pore pressures in a porous seabed around breakwater heads were investigated. They conducted a parametric study to examine the effects of wave and soil characteristics and breakwater configuration on the wave-induced pore pressure around breakwater heads. They found that the wave-induced pore pressure at the breakwater head is greater than that of the trunk of a breakwater and the relative difference of wave-induced pore pressure between fully dynamic and quasi-static solutions is larger at the breakwater head than that of the trunk of a breakwater. Lou *et al*. (2015) have been developed two-dimensional numerical models and physical models to study the highly nonlinear interactions between waves and breakwaters. They have developed a multi-material arbitrary Lagrangian-Eulerian method to simulate the nonlinear interactions between nonlinear waves and elastic seawalls on a rubble-mound breakwater and validated it experimentally. Ketabdari *et al*. (2015) have numerically studied the effects of discontinuous submerged breakwaters over water surface elevation using MIKE21 software. They compared the result of discontinuous breakwater to a beach without breakwater and showed that the gap, intensely effects on surface elevation, from shoreline to offshore. Kundapura and Hegde (2017) have performed a comprehensive review to serve as a guide to the current state of the art knowledge in the application of soft computing techniques in breakwaters. This study aims to provide a detailed review of different soft computing techniques used in the prediction of performance of different breakwaters considering various combinations of input and response variables. Galiatsatou *et al.* (2018) presented an approach on implementing appropriate mitigation measures for the upgrade of rubble mound breakwaters protecting harbors against increasing future marine hazards and related escalating exposure to downtime risks. This approach is based on the reliability analysis of the studied structure coupled with economic optimization techniques. It includes the construction of probability distribution functions for all the stochastic variables of the marine climate (waves, storm surges, and sea level rise) for present and future conditions. The proposed methodology has been applied to an indicative rubble mound breakwater with an existing superstructure. The construction of a berm on the existing primary armor layer of the studied breakwater seems to be advantageous compared to other mitigation options.

Scour may threaten the stability of breakwaters and reduce their functionality. Hence, protection against scour can ensure breakwaters' performance. Pourzangbar *et al*. (2017) have used genetic programming (GP) and artificial neural networks (ANNs) to predict the maximum scour depth at breakwaters due to nonbreaking waves. The models have been built using the relative water depth at the toe, the Shields parameter, the nonbreaking wave steepness, and the reflection coefficient. The results indicate that the developed models perform significantly better than the empirical formulas derived from the small-scale model experiments. The GP model performs slightly better than the

ANNs model and also produces an acceptable and physically-sound equation to predict the maximum scour depth.

A conceptual estimate, also known as a top-down, order of magnitude, feasibility, or preliminary estimate, is the first serious effort made to predict the cost of the projects. A conceptual estimate is usually performed as part of the project feasibility study at the beginning of the project. This estimate is made with limited information on project scope and is usually made without geotechnical investigation, bathymetry plan, and basic and detailed designs. The conceptual estimate is an important predesign planning process and is used to know the budget for a project.

The aim of this paper is to propose an algorithm along with an analytical model and its computer application to estimate roughly the material quantities needed for the construction of breakwaters employing the design water depths that are adapted to the maximum draught of the specified design ship. The design water depth in harbor is defined by adding the maximum draught of the specified design ship to the minimum under keel clearance. The minimum under keel clearance can be calculated as one of the factors required to provide safe passage for a ship. This would allow the maximum water depth in entrance channel in harbor and near the head of breakwater to be calculated taking into account a ship's size, draught and nature of cargo. Many ship transits occur in the confined waters of ports and harbors where a minimum clearance can be defined and controlled. Many ports use whichever is the greater of a defined figure or 10% of a ship's draught as the minimum under keel clearance (NOREL NAV SUB Group (2012).

A simplified numerical simulation procedure is applied to calculate the wave characteristics and the quantity of breakwater construction materials. By calculating the weights and thicknesses of breakwater sections layers (core, filter layer and armor layer), considering the geometry of breakwaters, the transversal and longitudinal sections and also the area of the harbor basin needed to shelter the ships and jetties and applying the proposed linear-constant model (LCM) for waterdepth-length relationship, the quantity of materials required for construction of the breakwaters are estimated.

For construction management purposes and for making decisions, at the feasibility study and planning phases, rough estimates within an acceptable accuracy are adequate. Some simplifying assumptions, including the following items, are applied:

- A linear-constant waterdepth model together with a proposed section configuration for the breakwaters, which is customary for harbors, is considered.
- To calculate the quantity of materials, a linearly variable waterdepth (constant slope) and a constant waterdepth (zero slope), i.e. an LCM is applied to waterdepth-length relationship.

Since a simplified numerical simulation procedure is applied to calculate the wave characteristics and also a linear-constant waterdepth model together with a proposed section configuration for the breakwaters is employed to estimate the breakwater construction materials, the application of the proposed algorithm is limited to the conceptual estimation of materials' quantity of rubble-mound breakwaters constructed with similar section configuration and are suitable mainly for small ports.

2. Proposed algorithm

2.1 Computer programming

A computer program entitled Harbor Numerical Analysis Program "HaNAP" has been generated by the authors. HaNAP has three main subprograms: Wave Simulation Program (WaSiP), Material

Quantity Estimation (MaQE), Harbor Location Finder (HaLoFin). WaSiP has been developed to simulate the wave characteristics. MaQE is applied to estimate the materials needed for the core, toe berm filter and armor layers of breakwaters, respectively. HaLoFin finds the best location for new harbors globally by applying a proposed analytical model considering the total transportation expenses in land and sea. The transportation price, the distribution of population, capacities of existing harbors and import/export cargo demands are considered as the main parameters. To find the distance between the harbors and cities, the spherical and geographical coordinate systems are applied. Since the real lengths of the roadways, railways and seaways between two points on the Earth are more than the minimum mathematical distance between that two points, a distance factor is proposed to estimate the real road lengths by multiplying the distance factor to the direct mathematical distances (shortest) between two points on the Earth surface, alternatively the program accepts the real distances directly (Nouban and Sadeghi 2014, Nouban 2015).

2.2 Waves numerical simulation applied in WaSiP

To estimate the quantity of breakwater material the formulas proposed by Bretschneider are used to estimate the wave characteristics in deepwater, then by considering the factors related to the effects of the seabed on the waves (shoaling, refraction and breaking phenomena), the wave characteristics in the transitional and shallow waters are simulated numerically (US Army Coastal Engineering Research Center 1980, Sadeghi 2008, Sadeghi 2007, Sadeghi K and Nouban 2013). This numerical simulation has been verified by comparison with the recorded waves in Caspian Sea waters.

2.2.1 Adopting spherical and geographical coordinates to calculate fetch length

A formulation is adopted to find the direct fetch lengths, applying the followings:

- The spherical coordinate system is employed to find the distance between the two points located at the beginning and the end points of the fetch.
- The geographical coordinates (altitude, longitude, and latitude) of all the required points are found using the Google Earth Website or the like.
- The spherical and geographical coordinates of a point P are illustrated in Fig. 1.
- The curved distance between the beginning point P_i and the end point P_j on the fetch (D_{ij}) are calculated by using the formulas given in this paper (see Fig. 2).

To find the wind direct fetch length, the spherical coordinate system is adopted. The distance between two points P_i and P_j is presented as follows.

The coordinates of a point P_i in the spherical coordinate system are defined as follows

$$x_i = R \sin\theta_i \cos\phi_i \tag{1}$$

$$y_i = R \sin\theta_i \sin\phi_i \tag{2}$$

$$z_i = R \cos\theta_i \tag{3}$$

where:

R: Radius of the sphere,

θ_i: Angle between the line joining point Pi on the sphere surface to the center of the sphere and z-axis.

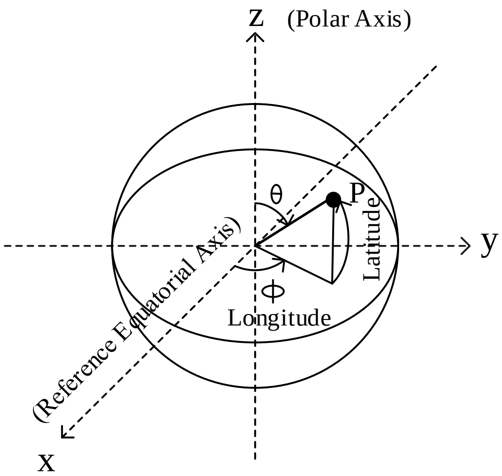

Fig. 1 Spherical and geographical coordinates of a point P

ϕ_i: Angle between the projection of the line joining a point on the sphere surface to the center of the sphere and x-axis (Surowski 1989).

The orientation of this coordinate system is considered as follows:

- The origin is at the center of the Earth,
- The x-axis passes through the Prime Meridian (0° longitude),
- The xy-plane contains the Earth's equator,
- The positive z-axis passes through the North Pole.

The two points $P_i(R_i, \Theta_i, \phi_i)$ and $P_j(R_j, \Theta_j, \phi_j)$ determined in spherical coordinates can be determined in the Cartesian coordinates of $P_i(x_i, y_i, z_i)$ and $P_j(x_j, y_j, z_j)$. The Euclidian distance δ_{ij} between Pi and P_j is given by the three-dimensional Pythagorean Theorem

$$\delta_{ij} = \left\{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2 + \left(z_j - z_i\right)^2\right\}^{1/2} \tag{4}$$

Converting the Cartesian coordinates to spherical coordinates gives

$$\delta_{ij} = R\left\{2 - 2sin\theta_i sin\theta_j \cos\left(\phi_i - \phi_j\right) - 2cos\theta_i cos\theta_j\right\}^{1/2} \tag{5}$$

where:

R: Radius of the Earth in sea areas,

θ_i: Angle between the line joining point Pi to the center of the Earth and z-axis passing the Earth's poles. The latitudes of the point Pi (λ_i) equals ($\pi/2 - \theta_i$),

θ_j: Angle between the line joining point Pj to the center of the Earth and z-axis passing the Earth's poles. The latitudes of the point Pi (λ_j) equals ($\pi/2 - \theta_j$),

ϕ_i: Longitude of the points Pi,

ϕ_j: Longitude of the point Pj.

The distance D_{ij} between Pi and Pj along the surface of the Earth (i.e., the arc length along the related sector) as shown in Fig. 2 can be found as follows (Surowski 1989):

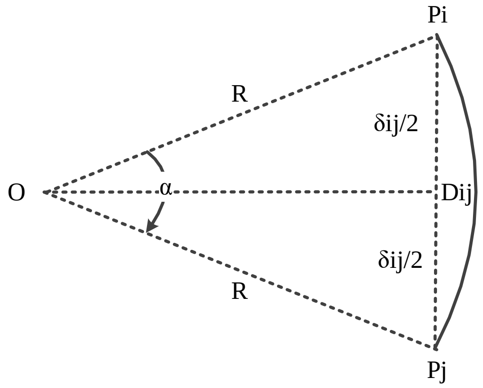

Fig. 2 The distance D_{ij} between Pi and Pj along the surface of the Earth

From Fig. 2

$$\sin\left(\frac{\alpha}{2}\right) = \frac{\delta_{ij}}{2R} \tag{6}$$

where α represents the angle between the lines joining points Pi and Pj to the center of the Earth. Since

$$\sin(\alpha) = 2\sin\left(\frac{\alpha}{2}\right)\cos\left(\frac{\alpha}{2}\right) = \left(\frac{\delta_{ij}}{R}\right)\left[1-\left(\frac{\delta_{ij}}{2R}\right)^2\right]^{1/2} = \left(\frac{\delta_{ij}}{2R^2}\right)\left[4R^2 - \delta_{ij}{}^2\right]^{1/2} \tag{7}$$

Therefore

$$D_{ij} = R\alpha = R\ sin^{-1}\left[\frac{\delta_{ij}}{2R^2}\left(4R^2 - \delta_{ij}{}^2\right)^{1/2}\right] \tag{8}$$

The above calculations assume a spherical Earth and ignore any ellipsoidal effects. This is accurate enough and results in errors of smaller than 0.3%).

The Fetch length (F) between two points P_i and P_j along the sea surface of the Earth is then

$$F = R\ sin^{-1}\left[\frac{\delta_{ij}}{2R^2}\left(4R^2 - \delta_{ij}{}^2\right)^{1/2}\right] \tag{9}$$

δ_{ij} is given in Eq. (5) and for sea areas, it is typical to use a fixed value for R equal to the average radius of the Earth (R = 6,378 Km) (Surowski 1989, Earth Fact Sheet 2015). Thus, fetch lengths are calculated assuming a spherical Earth.

2.2.2 Formulas used in WaSiP to simulate waves in deepwater

In WaSiP the wave characteristics are simulated using wave data and seabed specifications.

The Bretschneider formulas are employed in the numerical simulation to calculate the wave height, wavelength, wave period, wind duration to generate the wave height/period with the same fetch length and the other wave characteristics in deepwater for different wind durations and different fetch lengths. WaSiP considers the governing parameter (wind duration or fetch length) for the limited wind duration case or the limited fetch case in the calculation of the wave characteristics, respectively. This is carried out by calculating an imaginary equivalent fetch length for the wind duration by applying the wind duration formula, comparing it with the physical fetch length, selecting the lesser value of these two fetch lengths and apply it in the other formulas for calculating the wave characteristics values. (Sadeghi 2008, Sadeghi 1989, Sadeghi 2007a, Sadeghi and Nouban 2013)

The spectral wave height, average highest 10% wave height ($H_{10\%}$), the peak spectral period, the significant wave period are calculated employing the related formulas.

The effects of the sea bottom on the wave characteristics such as refraction, shoaling and wave breaking conditions are also included in the numerical simulation.

2.3 Analytical model to calculate breakwaters' material quantities

2.3.1 Calculation of armor layer, filter layer, and core material weights

In this algorithm, the Hudson equation, (Eq. (10)) (US Army Corps of Engineers, 2011) is employed to calculate the required weight of armor blocks necessary to provide satisfactory stability and protection against storm waves.

$$W = \frac{w_r \ . H^3}{K_D \ . (S_r - 1)^3 . Cot\theta} \tag{10}$$

where:

W: Design weight of an armor unit (Ton),

w_r: Specific weight of the armor units (Ton/m^3),

H: Design wave height at the toe of the breakwater (m),

K_D: Stability coefficient (US Army Corps of Engineers, 2011),

$S_r = \rho_r/\rho_w$, where ρ_r and ρ_w represent the densities of armor unit and seawater, respectively,

$Cot\theta$: Slope of the armor layer.

The weights of the layers of a section of the breakwater, recommended by the US Army Corps of Engineers (2011) are used in the estimation of material quantities. Estimation of weights of other layers (bedding layer, core and filter layer) for a section of the breakwater is performed by applying the values shown in the employed configuration given in Fig. 3.

The thickness of the armor and filter layers are calculated applying Eqs. (11) and (12), respectively (US Army Corps of Engineers, 2011)

$$r_a = nk_\Delta (\frac{W}{w_a})^{1/3} \tag{11}$$

$$r_f = nk_\Delta (\frac{W_f}{w_f})^{1/3} \tag{12}$$

where $W_f = {}^{W}/_{10}$; r_a and r_f represent the average thicknesses of the armor and filter layers, respectively; n represents the number of concrete or quarry stone used in the armor layer or filter layer thicknesses (normally n equals to 2); W_f represents the weights of a single filter layer unit; w_a and w_f represent the specific weights of the material of armor and filter units, respectively.

The placing density (the number of armor blocks per square meter) is estimated using Eq. (13) (US Army Corps of Engineers, 2011)

$$\frac{N_a}{A} = nk_\Delta(1 - \frac{P}{100})(\frac{w_a}{W})^{2/3} \tag{13}$$

where N_a represents the required number of armor units for a given surface area A. The values of the layer coefficient k_Δ and the cover layer average porosity P are employed as given by the U.S. Army Corps of Engineers (US Army Corps of Engineers, 2011).

2.3.2 Proposed LCM employed in MaQE

Employed typical section for rubble-mound breakwaters

The typical section employed for the trunk of a breakwater is illustrated in Fig. 3. The employed section is suitable for the breakwaters constructing from the landside, using dump trucks for transporting the materials to the breakwater. The top level of the core is considered at the maximum design sea water level, i.e., mean high water level (MHWL). Selection of this level enables trucks to work at a dry level on the core for almost all time and saves materials and time as well as prevents to construct a tall breakwater. This is practically feasible and is a normal practice in the construction of breakwaters. (Sadeghi 1989, 2001, Nouban and Sadeghi 2014, Nouban 2015).

Estimation of the weights and the quantities are performed by applying the configuration given in Fig. 3, which is adapted to those recommended by US Army Corps of Engineers (2011).

Proposed formulation to estimate the material quantities

Basic assumptions:

To estimate the material quantities for breakwater of harbors, a procedure considering a linear-constant relationship between waterdepth and the distance from the shoreline, as well as employing the typical section for breakwaters, is proposed as follows.

Areas of the typical section:

The area of the core, filter layer, and toe berm as well as armor layer (A_c, A_f and A_a) for the employed typical section shown in Fig. 3, is as follows

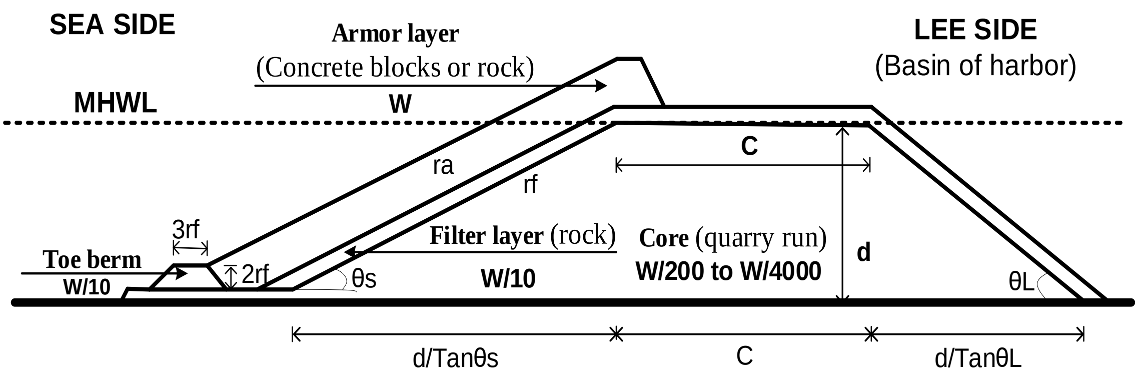

Fig. 3 Employed typical section

$$A_c = (d)\left[C + \left(\frac{d}{2}\right)\left(\frac{1}{Tan\theta_S} + \frac{1}{Tan\theta_L}\right)\right] = (d)\left[C + \left(\frac{d}{2}\right)(Cot\theta_S + Cot\theta_L)\right] \tag{14}$$

$$A_f = r_f[C + (d)\left(\frac{1}{Sin\theta_S} + \frac{1}{Sin\theta_L}\right) + 10r_f] \tag{15}$$

$$A_a = r_a[(d)\left(\frac{1}{Sin\theta_S}\right) + 3r_a] \tag{16}$$

where:

d: Waterdepth (from MHWL to seabed)
C: Crest width of core
θ_s: Slope angle of armor and filter layers in seaward side
θ_L: Slope angle of the filter layer in the leeward side
r_a: Thickness of armor layer
r_f: Thickness of filter layer

Equivalent lengths of breakwaters:

In calculations, two types of waterdepths are considered for the breakwaters: a linearly increasing waterdepth (constant slope) and a constant waterdepth (zero slopes) as shown in Fig. 4.

The following lengths are considered for the harbors with linear-constant waterdepth model:

L_1: Length of the part of the main breakwater constructed on the seabed with a slope of α,
L_2: Length of the part of the main breakwater constructed in a constant waterdepth d,
L_3: Length of the part of lee breakwater constructed on the seabed with a slope of α,
L_4: Length of the part of lee breakwater constructed in a constant waterdepth d,

As shown in Fig. 5, the area of the section of core (A_c) changes non-linearly versus waterdepth, and the area at waterdepth d/2 is less than half of the average area of the entire length.

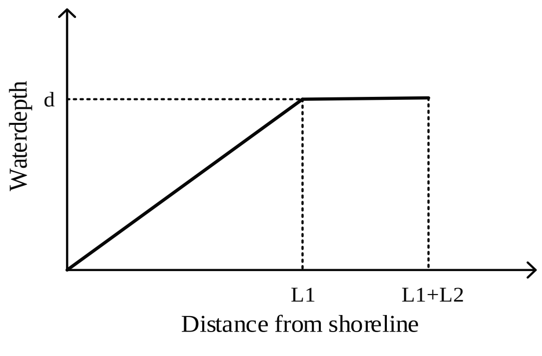

Fig. 4 Proposed linear-constant waterdepth model

To calculate the volume of the materials of core between waterdepth zero and waterdepth d, half of the section area at waterdepth d, multiply to the length of the breakwater and a reduction factor K_R is considered.

For a breakwater with $Cot\theta_S = \ Cot\theta_L = 1.5$, using Eq. (14), gives

$$A_{c,0} = 0 \qquad \text{(for waterdepth 0)} \tag{17}$$

$$A_{c,\frac{d}{2}} = \left(\frac{d}{2}\right)\left[C + \left(\frac{3d}{4}\right)\right] \qquad \left(\text{for waterdepth}\,\frac{\mathrm{d}}{2}\right) \tag{18}$$

$$A_{c,d} = (d)\left[C + \left(\frac{3d}{2}\right)\right] \qquad \text{(for waterdepth d)} \tag{19}$$

In Fig. 5, the changes in the area of core ($A_{c,d}$) versus waterdepth (d) considering C = 7 m, $Cot\theta_S = \ Cot\theta_L = 1.5$ are shown.

As this figure illustrates, the core area increases nonlinearly in a quadratic form when waterdepth increases. This is one reason that in this research a reduction factor K_R to the average area for the middle section (at waterdepth d/2) between zero waterdepth and waterdepth d for the core is adopted. Thus, the proposed reduction factor to the average area is defined as follows

$$K_R = \frac{A_{c,\frac{d}{2}}}{\frac{(A_{c,d}+A_{c,0})}{2}} = \frac{C + (\frac{d}{2})\left(\frac{Cot\theta_S+Cot\theta_L}{2}\right)}{C + (d)\left(\frac{Cot\theta_S+Cot\theta_L}{2}\right)} \tag{20}$$

The reduction factor to the average area (K_R) for different waterdepths (d) considering C = 7 m and $Cot\theta_S = \ Cot\theta_L = 1.5$ is shown in Fig. 6.

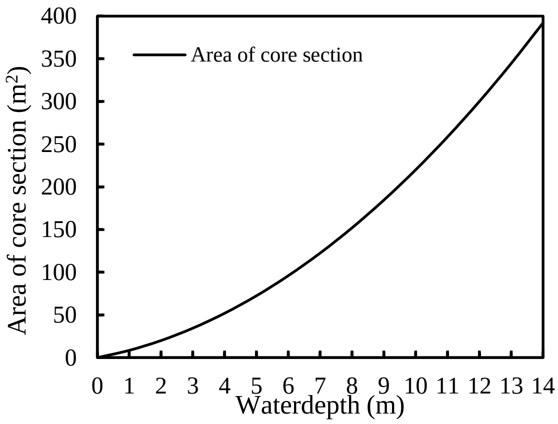

Fig. 5 Area of core section area versus waterdepth

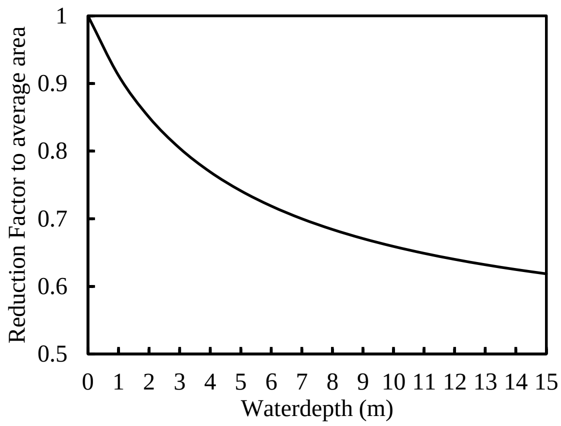

Fig. 6 Reduction factor to the average area (K_R) for different waterdepths

As this figure demonstrates, the reduction factor to the average area (K_R) for core decreases nonlinearly from 1 (at zero waterdepth). K_R has a value ranging from 1 to 0.5 from very shallow water to very deep water, respectively.

To calculate the total volume for core, in the linear-constant waterdepth case, the total equivalent length by applying a constant section at a waterdepth of "d", for the main and lee breakwaters, is found as follows

$$L_{eq,t} = (0.5K_{R1}L_1 + L_2 + 0.5K_{R3}L_3 + L_4) \tag{21}$$

where $L_{eq,t}$ represents the total equivalent length used to calculate the material volumes assuming that the entire breakwater is constructed in a waterdepth d.

<u>*Analytical model of core, filter and armor layers' weights:*</u>

The core volume (V_c) for the employed typical section is

$$V_c = (d_2)(0.5\mathrm{K}_{R1}\mathrm{L}_1 + \mathrm{L}_2)\left[C + \left(\frac{d_2}{2}\right)(Cot\theta_S + \ Cot\theta_L)\right] + (d_4)(0.5\mathrm{K}_{R3}\mathrm{L}_3 + \mathrm{L}_4)[C + (\frac{d_4}{2})(Cot\theta_S + \ Cot\theta_L)] \tag{22}$$

For the filter and armor layers, since their volume variation versus waterdepth are linear, $K_R = 1$. Filter and armor layer volumes (V_f and V_a) for the employed typical section are as follows

$$V_f = (r_f)[0.5L_1 + L_2 + 0.5L_3 + L_4][C + (d)\left(\frac{1}{Sin\theta_S} + \frac{1}{Sin\theta_L}\right) + 10r_f] \tag{23}$$

$$V_a = (r_a)(0.5L_1 + L_2 + 0.5L_3 + L_4)[(d)\left(\frac{1}{Sin\theta_S}\right) + 3r_a] \tag{24}$$

The crest of the breakwater should be wide enough to accommodate the construction and maintenance equipment used during the construction and operation periods on the breakwater. A crest width (C) of 7 m is assumed for the top level of core. This allows for the passing two trucks side-by-side to each other during the construction period. To reduce the quantity of materials used in the core and filter layer, as an alternative it is possible to use a crest width of 4m for the top level of the core (C) along with a number of parking places constructed every 50 meters to allow two trucks pass side-by-side.

The thicknesses of the armor and filter layers are found by applying Eqs. (11) and (12), respectively.

Core and filter total weights (W_{ct} *and* W_{ft}) for the employed typical section are given below

$$W_{ct} = w_c \Big\{(d_2)[(0.5\mathrm{K}_{R1}\mathrm{L}_1 + \mathrm{L}_2)]\left[C + \left(\frac{d_2}{2}\right)(Cot\theta_S + Cot\theta_L)\right] + (d_4)[(0.5\mathrm{K}_{R3}\mathrm{L}_3 + \mathrm{L}_4)][C + (\frac{d_4}{2})(Cot\theta_S + Cot\theta_L)]\Big\} \tag{25}$$

$$W_{ft} = w_f\left(1 - \frac{p}{100}\right)(r_f)(0.5L_1 + L_2 + 0.5L_3 + L_4)[C + (d)\left(\frac{1}{Sin\theta_S} + \frac{1}{Sin\theta_L}\right) + 10r_f] \tag{26}$$

Armor layer total weight (W_{at}) for the employed typical section is

$$W_{at} = w_a\left(1 - \frac{p}{100}\right)(r_a)(0.5L_1 + L_2 + 0.5L_3 + L_4)[(d)\left(\frac{1}{Sin\theta_S}\right) + 3r_a] \tag{27}$$

2.4 Multi-linear model (MLM) developed to estimate the material quantities

The formulation for estimation of material quantities of breakwaters for a harbor, considering multi-linear waterdepth model and the proposed section is submitted as follows:

2.4.1 Areas of the typical section "i"

The cross-section areas of core, filter layer, and armor layer ($A_{c,i}$, $A_{f,i}$ and $A_{a,i}$) for employed typical section "i" are as follows

$$A_{c,i} = (d_i)[C + (\frac{d_i}{2})(Cot\theta_S + Cot\theta_L)] \tag{28}$$

$$A_{f,i} = r_f[C + (d_i)\left(\frac{1}{Sin\theta_S} + \frac{1}{Sin\theta_L}\right) + 10r_f] \tag{29}$$

$$A_{a,i} = r_a[(d_i)\left(\frac{1}{Sin\theta_S}\right) + 3r_a] \tag{30}$$

where:

di: Waterdepth (from MHWL" to seabed) at section "i"

2.4.2 Analytical model of the lengths and weights of breakwaters employing MLM

Fig. 7, shows the MLM curve for the relationship between waterdepth (d_i) and distance from the shoreline (X_i). This curve is used to estimate the material quantity required to construct the breakwater.

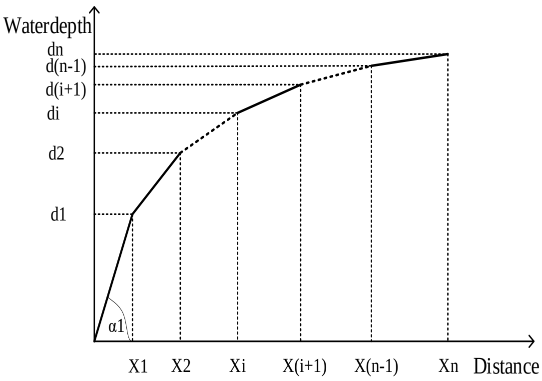

Fig. 7 MLM curve versus distance from the shoreline

L(i+1) is calculated using Eq. (31)

$$L_{(i+1)} = X_{(i+1)} - X_i = \frac{d_{(i+1)} - d_i}{Tan\alpha_{(i+1)}} \tag{31}$$

where:

$L_{(i+1)}$ represents the length of the part of a breakwater constructed with a slope of $\alpha_{(i+1)}$ on the seabed between sections "i" and "i+1" having waterdepths d_i and $d_{(i+1)}$, respectively.

Using L_t to denote the total breakwater length assumed to calculate the volume of material required, and then the total length of the main breakwater is given by:

$$L_{t,M} = \sum_{i=0}^{i=m} L_{(i+1)} = \sum_{i=0}^{i=m} \left(\frac{d_{(i+1)} - d_i}{Tan\alpha_{(i+1)}}\right) \tag{32}$$

Similarly, the total length of the lee breakwater is

$$L_{t,L} = \sum_{j=0}^{j=n} L_{(j+1)} = \sum_{j=0}^{j=n} \left(\frac{d_{(j+1)} - d_j}{Tan\alpha_{(j+1)}}\right) \tag{33}$$

Therefore, the total equivalent lengths of breakwaters (main and lee), is

$$L_t = \sum_{i=0}^{i=m} L_{(i+1)} + \sum_{j=0}^{j=n} L_{(j+1)} = \sum_{i=0}^{i=m} \left(\frac{d_{(i+1)} - d_i}{Tan\alpha_{(i+1)}}\right) + \sum_{j=0}^{j=n} \left(\frac{d_{(j+1)} - d_j}{Tan\alpha_{(j+1)}}\right) \tag{34}$$

The core, filter layer and armor layer volumes (V_c, V_f and V_a) are as follows

$$V_c = \sum_{i=0}^{i=m} L_{(i+1)} \left(\frac{A_{c,i} + A_{c,(i+1)}}{2}\right) + \sum_{j=0}^{j=n} L_{(j+1)} \left(\frac{A_{c,j} + A_{c,(j+1)}}{2}\right) \tag{35}$$

$$V_f = \sum_{i=0}^{i=m} L_{(i+1)} \left(\frac{A_{f,i} + A_{f,(i+1)}}{2}\right) + \sum_{j=0}^{j=n} L_{(j+1)} \left(\frac{A_{f,j} + A_{f,(j+1)}}{2}\right) \tag{36}$$

$$V_a = \sum_{i=0}^{i=m} L_{(i+1)} \left(\frac{A_{a,i} + A_{a,(i+1)}}{2}\right) + \sum_{j=0}^{j=n} L_{(j+1)} \left(\frac{A_{a,j} + A_{a,(j+1)}}{2}\right) \tag{37}$$

The core, filter layer and armor layer total weights (W_{ct}, W_{ft} and W_{at}):

$$W_{ct} = w_c V_c \tag{38}$$

$$W_{ft} = w_f \left(1 - \frac{p}{100}\right) V_f \tag{39}$$

$$W_{at} = w_a \left(1 - \frac{p}{100}\right) V_a \tag{40}$$

2.5. Application of HaNAP

2.5.1. Verification of wave simulation using WaSiP

To confirm the validity and accuracy of the numerical wave simulation, the results obtained were compared with actual results obtained for the Iranian waters of Caspian Sea. The wave characteristics were simulated based on available wind, air, and seawater temperature data recorded by Khazar Oceanography Buoy, installed by Khazar Exploration of Petroleum Company from Caspian Sea (KEPCO 2001). The buoy is installed at a waterdepth of 35 m and 30 km away from the Neka harbor in Iranian coasts.

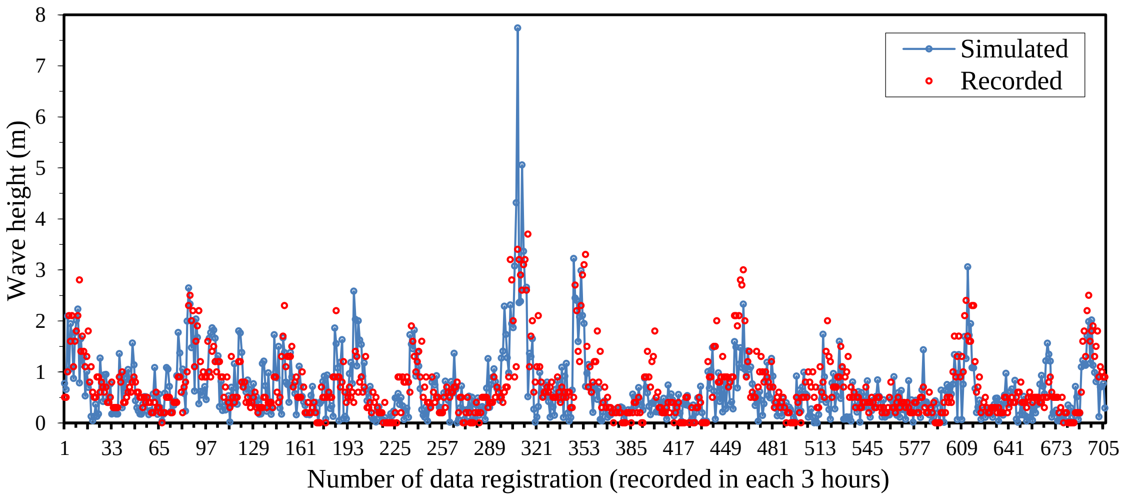

Fig. 8 Comparison of simulated and recorded wave heights

The waves simulated by the developed algorithm were verified by the data collected in Caspian Sea because of the availability of the data from the mentioned buoy, considering that the formulas proposed by Bretschneider are independent of the location and can be used everywhere. The results of the comparison of simulated and recorded wave heights for the period of February 1989 to April 1989 are shown in Fig. 8.

As this figure demonstrates and the application of the regression analysis illustrates a determination factor (R-squared) of $R^2 = 0.83$, there is an acceptable agreement between the simulated and recorded wave heights, especially for the conceptual design and feasibility study that are targeted in this paper. This conclusion accords to Henseler (2009) and some other researchers who state R^2 with 0.75, 0.50, and 0.25 are described as substantial, moderate and weak respectively.

2.5.2 Application of material quantity estimation applying MaQE

To examine the validity of the proposed model for estimating breakwater material quantities, four harbors, constructed on the coasts of Kish Island, Tunb Island, Langeh and Larak, located in Iran coasts in Persian Gulf were selected (PMO, 1974a, 1974b, 1995, 2006). Considering that there are more available geometry and bathymetry data for harbors in Persian Gulf compared to Caspian Sea. The proposed model may be applied in the cases in which the bathymetry map at the location of the harbor is not available and only the maximum waterdepth is known. This model is applicable mainly for conceptual estimation.

Figs. 9 and 10 illustrate the cumulative weights of core and layers of the main and lee breakwaters, using MLM for Kish harbor.

In Figs. 11 to 14, the total weight, core weight, filter layer weight and armor layer weight of the four examined harbors in Persian Gulf are compared applying LCM and MLM.

Table 1 presents the percentages of overestimation or underestimation of the weights for core, filter layer, armor layer and total weights of the four examined harbors applying LMC compared to MLM.

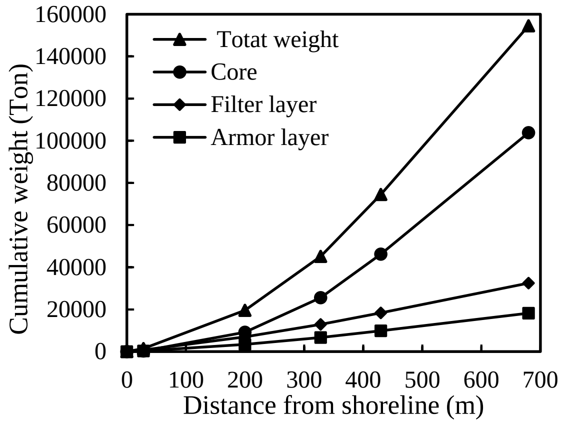

Fig. 9 Cumulative weights of core and layers of the main breakwater of Kish harbor, using MLM

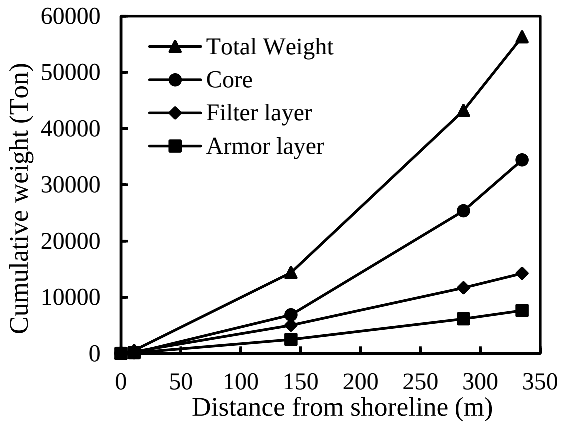

Fig. 10 Cumulative weights of core and layers of the lee breakwater of Kish harbor, using MLM

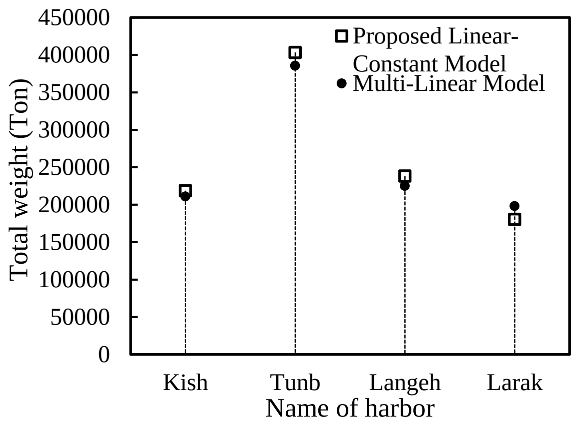

Fig. 11 Total weight of breakwaters of the four examined harbors

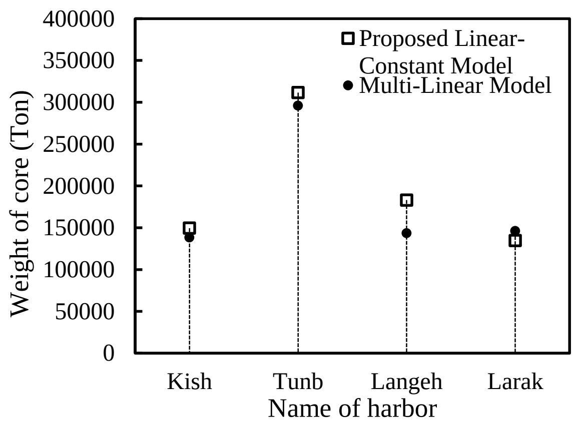

Fig. 12 Core weights of breakwaters of the four examined harbors

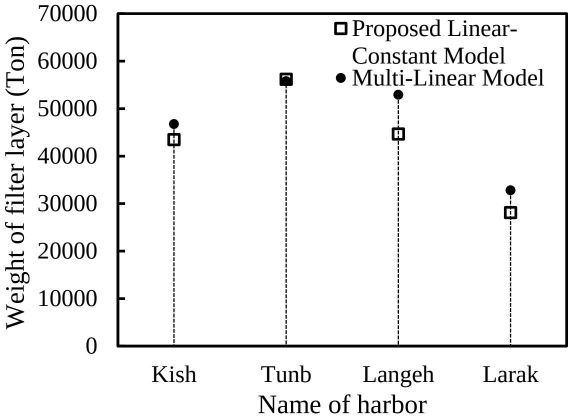

Fig. 13 Filter layer weights of breakwaters of the four examined harbors

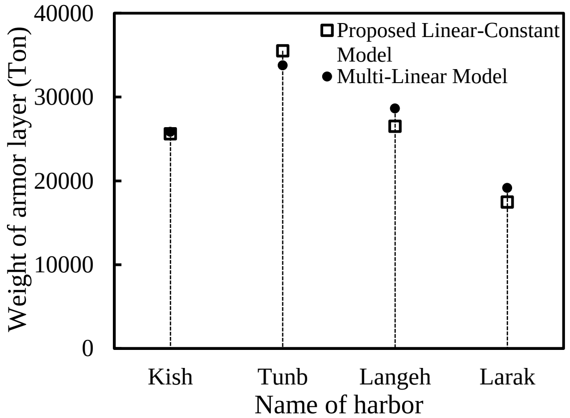

Fig. 14 Armor layer weights of breakwaters of the four examined harbors

Table 1 Percentages of over/underestimation (+/-) of weights using LCM

Item no.	Harbor name	Core (%)	Filter layer (%)	Armor layer (%)	Total weight (%)
1	Kish	+8.2	-7.0	-0.9	+3.7
2	Tunb	+5.3	+0.7	+5.2	+4.6
3	Langeh	+16.6	-15.6	-7.4	+5.9
4	Larak	-7.8	-14.3	-8.9	-9.0
	Average error	+5.5	-9.0	- 3	+ 1.3

As it can be seen from Table 2, the proposed LCM underestimates the filter layer weight about 9% and armor layer weight about 3%. The average overestimation for the weight of the core material is about 5.5% and the total weight of breakwater less than 2%. It can be concluded that for the conceptual estimates and in the feasibility study phase, the accuracy of the proposed LCM is acceptable, and the proposed algorithm is a good tool to be used for making the conceptual estimation in harbor projects and especially for total weight and core material estimates. As the quantities estimated for the filter and armor layers are underestimated in most cases.

3. Conclusions

A simplified calculation procedure and an analytical simplified model are proposed to calculate the wave characteristics and to estimate the approximate material quantities needed to build harbors constructed of rubble-mound breakwaters.

To evaluate the validity of the wave simulation procedure employed, the results were compared to real conditions found in the waters of Caspian Sea. The wave characteristics were simulated and the comparison between the simulated and recorded wave heights indicates that there is a good agreement between the simulated and recorded wave heights.

The developed computer applications to simulate numerically the wave characteristics and to calculate the rubble-mound structures' layers is suitable for the preliminary designs and rough estimation purposes in the project feasibility phase.

To validate the formulation proposed for estimation of material quantities of breakwaters, a case study was applied to four harbors located in Iran coasts in Persian Gulf. The estimated weights using the proposed LCM and MLM were compared using the bathymetry maps and layouts of these harbors. This comparison shows that considering the acceptable accuracies in the conceptual estimates, the proposed algorithm is a good tool to be used in the feasibility phase of a harbor project. This model is applicable for the harbors with linear-constant waterdepth model and for the cases that the bathymetry map at the location of the harbor is not available and only the maximum waterdepth is known from the draught of the design ship.

Using the proposed model helps the clients, at the planning phase of a harbor, to obtain a quick estimation of material quantities.

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