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RUBBLE-MOUND BREAKWATER CONSTRUCTION SIMULATION

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Abstract: Rubble-mound breakwater is the most typical group of breakwaters with three main sections including core, filter, and armor. Marine structures construction is considered one of the expensive operations compared to other projects, therefore cost efficiency and productivity can play a significant role in breakwaters construction management. The objective of this research is to simulate this type of structure construction process addressing real operation complexity to find the optimum resource quantity and increase production rate and reduce construction costs. In this study, the cyclic construction process of the natural rubble-mound breakwater is studied through MicroCYCLONE and EZstrobe simulation programs. Nineteen similar breakwaters are selected as a case study for which simulation models are developed and validated through available field data. The efficiency of the developed models was verified by 90% and 95% for MicroCYCLONE and EZstrobe respectively. The results of this research indicate that from both cost and production point of views for projects with 10 km hauling distance, using 2 loaders for loading at mine, 12 trucks for hauling materials from mine to site and 3 backhoes for placement would be the best alternative. For projects with 15 km and 30 km hauling distances, the results indicate that it is more efficient to use 14 and 19 trucks respectively. Production rate analysis for different scenarios will provide a means to evaluate the effectiveness of resource allocation and apply necessary changes to obtain the optimum results in terms of production and cost efficiency.

1 INTRODUCTION

Breakwater is a structure forming an artificial harbor to protect the shore from severe wave motions (Dhinakaran et al. 2012; Takahashi 2002). Breakwaters have different varieties; however, as a general classification, they can be categorized according to their configuration i.e. mound or vertical types (Kaplan and Pape 1950). Rubble-mound breakwater is the most common type due to the simplicity of construction processes and equipment demand. Generally, construction of marine structures is considered as an expensive operation compared to other construction projects, leading to a key role of cost efficiency and productivity in breakwater construction management. Construction processes of rubble-mound breakwaters are often cyclic and repetitive. Thus, any enhancement in the production rate of the system has a significant impact on project performance and the overall cost.

Simulation is considered as the most common technique in construction operations management (Law and Kelton 2000). Modern computers help to increase simulation efficiency and speed (Wang and Halpin 2004). As a solution, construction simulation provides a means to highlight the existing problems and improve system productivity (Halpin and Martinez 1999). Some of the existing methodologies in the simulation of construction processes can be named as CYCLONE (CYClic Operations NEtwork), STROBOSCOPE

(State and ResOurce-Based Simulation of COnstruction ProcEsses), Symphony and DISCO (Dynamic Interface for Simulation of Construction Operations).

The closest construction processes to the rubber-mound breakwater might be earth moving activities which are studied in several research works (Martínez 1998; Marzouk and Moselhi 2002; Montaser et al. 2012; Siadat and Ruwanpura 2013; Shi and AbouRizk 1998). However, specific complexities involved in breakwater operation, as well as construction requirements, call for addressing several additional details. From modeling point of view, material heterogeneity should be considered in loading and hauling tasks. From processing point of view, breakwater operation in filter/armor placement as the most critical and time-consuming task is significantly different rather than earth moving process.

The main objective of this research is to propose a productivity simulation model for typical rubble-mound breakwaters through MicroCYCLONE and EZstrobe techniques. The simulation model is developed based on the collected data from nineteen similar rubble-mound breakwaters. Outputs are deployed to obtain optimum resource allocation to increase production rate and reduce the costs. The simulation results are presented based on multiple scenarios for three hauling distances of 10, 15 and 30 kilometers from mine to the construction site. This research will guide marine engineers and project managers to plan for operation in advance, increase production rate and reduce the cost of rubble-mound breakwater construction by choosing a proper resource allocation for different scenarios and hauling distances.

2 BACKGROUND

Construction simulation is considered as a powerful tool for different objectives such as risk analysis, resource planning, design and analysis of construction methods and site planning besides productivity analysis (Sawhney et al. 1998). One of the earliest methods of construction simulation was developed by Halpin (Halpin 1977) named CYCLONE (CYCLic Operations NEtwork). CYCLONE is counted as a practical means of simulation method due to providing clear and simple symbols besides presenting a quantitative way of viewing, planning, analyzing and controlling processes and operations (Ghanem and Kolailat ; Cheng et al. 2000). In fact, CYCLONE is considered as the first discrete event simulation (DES) system developed specializing in construction operations (Lee et al. 2010). Operations research-based discrete event simulation DES systems are applied to model construction processes and analyze their corresponding productivity at operation level (Lee et al. 2010). Application of this methodology has become much easier due to development of MicroCYCLONE as a computer program. This methodology focuses on resources and their interactions in which the resources move from one state to another (idle to active). Some examples for CYCLONE applications on different construction operations include earth moving (Halpin 1977), concrete placement (Alkoc and Erbatur 1997), driving piles (Zayed and Halpin 2004), steel construction process (Ghanem and Kolailat) and planning heavy construction processes (Vanegas et al. 1993). STROBOSCOPE is a programmable simulation technique which is used for simulation and modeling complex construction operations (Martinez and Ioannou 1999). Later EZstrobe was developed by Martinez to facilitate and simplify using STROBOSCOPE with a graphical format which is based on activity cycle diagrams (Martinez 2001). Some examples for applications of EZstrobe on construction modeling include concrete paving operations (Hassan and Gruber 2008), the productivity of yard trucks in port container terminal (Ahmed et al. 2014) and tunnel construction (Obeidat et al. 2006). The state of art shows few studies in the domain of breakwater construction simulation. One corresponds to a study published by Abraham et al. (Abraham et al. 1995) in which simulation of a specific type of rubble-mound breakwater is studied through a CYCLONE model, however, the model is limited to only 40 cycles due to limitations of then-current simulation methods. The other study corresponds to Singh and Hansbrough (Singh and Hansbrough 2014) in which construction of a sand-filled geotextile breakwater with grid mats is investigated for beach extension through developing an EZstrobe model from five construction projects. None of these studies focus on the construction of a typical rubble-mound breakwater despite its widespread practice and design. Also, the simulation results are not validated and compared to any field data leading to some doubts in the accuracy of the model. Thus, the necessity to conduct a study on simulation of construction operation of a typical rubble-mound breakwater is inevitable. In this research, simulation outputs are obtained and compared with two programs, i.e. MicroCYCLONE and EZstrobe and results are validated.

2.1 Rubble-mound breakwater construction processes

Depending on breakwater dimensions and type, the construction process and number of tasks may be complicated or simple. Design procedure alters a number of tasks, their correlation and the resources needed in construction operation. Usually, a rubble-mound breakwater consists of three main layers including core, filter, and armor as illustrated in Figure 1.

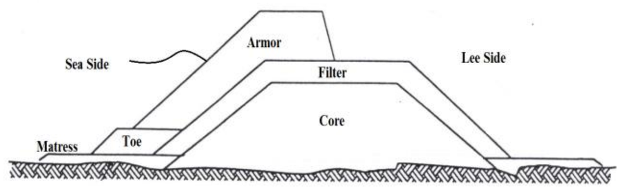


Figure1: Rubble-mound breakwater typical section

1) Stone preparation: The most common method for providing material is blasting. Based on the portion of specific stone material for each section, losing process should be designed regarding stone specification, blasting material and drilling equipment. Otherwise, it may impact project quality and productivity. 2) Loading trucks at mine: Loaders and sometimes backhoes are deployed for loading various kind of stones in a predetermined mine spot. Although loading seems to be a simple task, for more efficiency one source center is considered, leading to a more complicated simulation model in comparison to common earth moving projects. 3) Hauling and Returning: Project production rate may be impacted directly by this task. In addition to distance, road conditions, obstacles and the chosen route can change hauling time. In some projects, especially for long distance hauling operations and urban areas, marine transport can also be used. In small projects, the same sources (trucks) are used to transfer all material types. 4) Dumping: The core is usually dumped directly in place by truck guided by one spotter on land, however, marine equipment can also be used to increase the production rate. For filter and armor placement other equipment such as backhoe or crane is needed due to the considerably higher weight of stone materials. Also, the thickness of these layers is not high enough for direct dumping and most importantly these layers have a crucial role in providing breakwater stability during the life cycle. For filter and armor dumping operations, the truck should dump the material as close as possible to placement equipment (backhoe or crane). In some cases, due to space/time limitation or environmental conditions, stones are dumped out of breakwater construction location and are transferred again to the placement areas which impact production rate and is addressed in this study. 5) Placement: The most sensitive task in the construction process is placement and total production rate is highly dependent on this time-consuming task. Placement during construction of rubble-mound breakwaters can be carried out by land or marine based methods. In huge breakwater, it may be economical to use both methods. In general, using marine dumping (for core) or placement is a feasible and economical method for large breakwaters with enough water maneuvering depth. 5-1) Core placement: Direct dumping of core section leads to a steeper slope line; therefore, it is necessary to modify the placement line using a backhoe. 5-2) Filter placement: For other layers, usually direct dumping is not an accepted process. Depending on project section, stone weight and dimension usually the first machinery chosen is a backhoe. Clearly, for a deep breakwater crane and bucket are needed. 5-3) Armor placement: Generally, the process is similar to filter placement; however, due to the increase of weight and dimensions, a more powerful backhoe with enough boom length or crane is used. In severe environmental conditions and material limitations, the stone is replaced by precast concrete for armor layer. 6) Reloading in site: As mentioned earlier, it is not always possible to dump material directly on the predicted construction area due to space and equipment limitations as well as environmental conditions. Usually, a storage area is determined for dumping stone material near the placement area, leading to the additional tasks of reloading, hauling and dumping into the simulation model.

3 RESEARCH METHODOLOGY AND MODEL DEVELOPMENT

The methodology pursued in this research consists of four main phases as presented in Figure 2. These phases include, Phase I: Conducting literature review: This step involves studying rubber mound breakwater construction processes and reviewing simulation techniques performed in the domain of breakwater and other structures. Phase II: Model development: In this step construction operation is modeled through two well-known simulation tools (MicroCYCLONE and EZstrobe). The details of the developed simulation and the graphical model are highlighted in detail further. Phase III: Model implementation: In this step, the conditions of the case study are applied to MicroCYCLONE and EZstrobe models. Then the obtained results are utilized for validation purpose. Phase IV: Sensitivity analysis: This phase provides different scenarios for resource allocation along with production rate and estimated cost for each alternative. The results of this phase help researchers and project managers to compare different options and choose the optimum one in terms of cost and productivity.

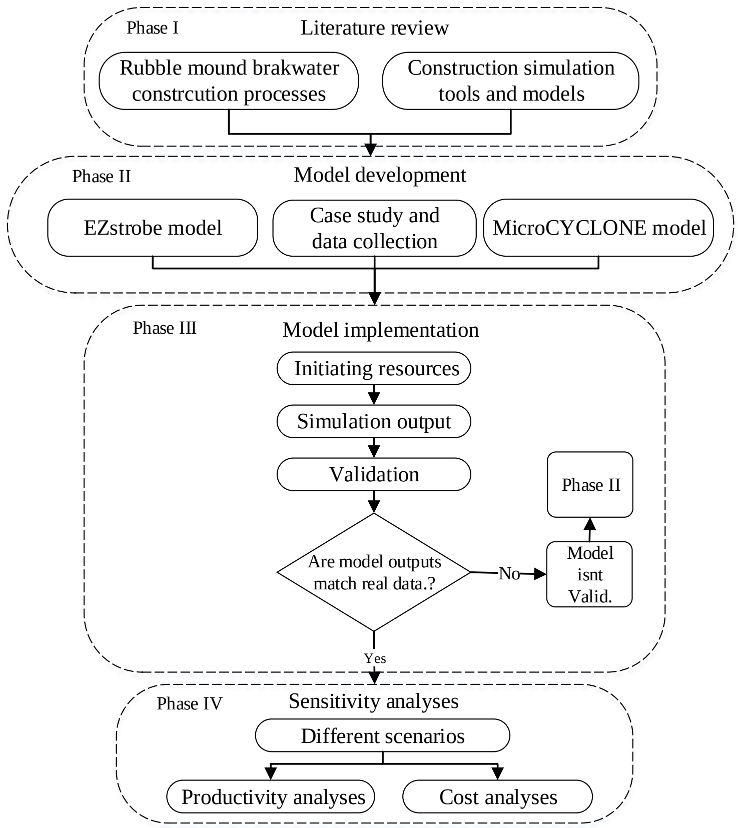


Figure 2: Simulation methodology of rubble-mound breakwater construction

4 CASE STUDY AND DATA COLLECTION

The case study of this research consists of numerous (nineteen) typical rubble-mound breakwaters in Persian Golf at the south of Iran which are approximately similar in dimensions, sections, environmental conditions and construction processes. Figures 3 and 4 illustrate the typical section and plan of the breakwaters. The operation includes construction of three main layers of core, filter, and armor. Rubble and stone production takes place in mine by blasting to which production rate is highly dependent upon some specific and complicated factors (e.g. blasting materials, mine conditions). In the current study, due to lack of data, this task is ignored and the research covers construction processes starting from truck loading. Low water depth and small section dimensions let construction teams complete core, filter, and armor placement tasks using a proper backhoe on site.

Fig.3

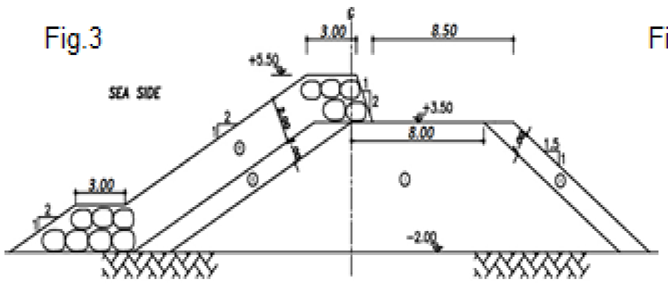
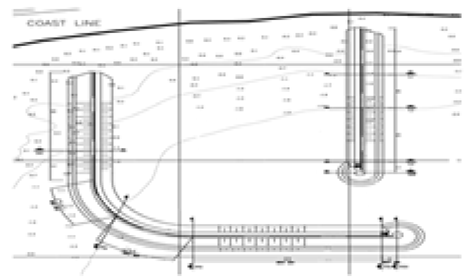


Fig. 4



Figures 3 and 4: Typical section and the plan of the case study

Regarding data collection the following steps were taken:

- Real productivity (m^3/week) for core, filter and armor placement of 19 similar breakwater construction projects were collected during a six-month period. This data is used to validate the results obtained from simulation modeling. 12, 5 and 2 of these projects have a hauling distance of 10, 15 and 30 kilometers to the mine respectively. Also, not convenient enough observations were filtered for model accuracy.

- A questionnaire was designed to gather experts' judgments in this field. The experienced engineers were asked to provide most common (A), optimistic (O) and pessimistic (P) durations of each task for all layers in different hauling distances. The questionnaire collects data based on a triangular distribution due to its advantage in ease of communication purpose with the experts (Zayed and Halpin 2004). Table 1 represents a questionnaire sample in this study. The tasks in the questionnaire include loading at the mine, hauling to the site, dumping in the site, placement and finally truck returning to the mine.

Table 1: Sample of expert questionnaire for cycle time estimates.

Project manager	Material	Loading (Min.)			Hauling (Min.)			Dumping (Min.)			Placement (Min.)		
with 14 years		O	A	P	O	A	P	O	A	P	O	A	P
of experience	Core	8	10	13	20	25	30	4	5	6	8	10	12
	Filter	3	5	10	20	25	30	4	4	5	18	20	30
	Armor	3	5	10	20	25	30	4	4	5	25	30	40

- Recorded loading task durations in the field for core, filter and the armor were collected. For more accuracy, this data was used as the input of simulation model for loading tasks. To obtain the best-fitted distribution of this task, @RISK software was used. The distributions that best fitted the entry data and satisfied Chi-square tests were obtained as exponential or uniform distributions for core, filter, and armor.

- With respect to experience and expert judgement, the probabilities of dumping material in storage area in site for core, filter and armor are considered as 15%, 50% and 80%, respectively.

- The average value of the most common, optimistic and pessimistic cases was estimated from the questionnaires (except loading task durations that are obtained from field data), and simulation model inputs were entered as a triangular distribution.

5 SIMULATION MODEL DEVELOPMENT

Generally, the final production rate of construction operation is influenced by some factors including:1) Mine productivity (stone quality, blasting material and output, the speed of separation process). 2) Hauling distance conditions (public or private road, road conditions). 3) Designated variety of stones and sections (designed slope of breakwater section, stone size diversity). 4) Environmental conditions. 5) Economic conditions. 6) Contractor experience and equipment. CYCLONE model is developed for this study to investigate rubble-mound simulation using MicroCYCLONE elements (Halpin and Riggs 1992). The construction process includes three main cycles for each section (core, filter, and armor) which can advance separately. Based on the designed section and task priorities, construction site needs three stone types in different and specific volumes. For instance, in breakwater section (as presented in Figure 3) for a 1-meter length of breakwater, the approximate volume of stone needed for core, filter, and armor are 100 m^3, 25 m^3 and 43 m^3, respectively. Therefore, during material production, loading, transportation and placement stages, this logic should be respected in modeling. In general, rubble-mound breakwater model is similar to that of earth moving operation in terms of activities sequence. However, this simulation model must address crucial details to represent real conditions in site. In the next section, these details are discussed.

5.1 Transferring Material to the site

As mentioned earlier the first task in the simulation model is loading material into the truck at the mine. Since for higher efficiency, both loader and truck machinery serve all layers, the model must be designed with a single loading center. Meanwhile, the number of loadings required for each component per unit length of the designed section and the capacity of trucks for each material type should be considered in modeling. Thus, the volume implemented for each component per unit length is calculated regarding Figure 3. Trucks with 14 m3 theoretical capacity are selected for hauling. Table 2 presents truck capacity as well as the required number of trucks for each layer in 1-meter length of the breakwater.

Table 2: Volume characteristics of breakwater components

Component	Designed volume(m^3/m)	Truck capacity(m^3)	No. of trucks/m
Core	97	12	8.15
Filter	25.1	11	2.28
Armor	43.2	10	4.32

According to this table, for each 4 trucks of the core, 2 trucks of armor, and 1 truck of filter should be loaded by single loading center and transferred to the construction site. To address this critical requirement, the simulation model starts with loading the core followed by armor and the filter, respectively. In real conditions, priority is given to core, filter and finally armor. However, in simulation model due to CYCLONE capabilities for addressing this single loading center requirements, priority is given to armor rather than the filter. Since placement of layers takes place one by one with enough lag time, and materials are sent to the site and placed continuously, this assumption does not impact output accuracy. Therefore, loading core and armor tasks are followed by two consolidate functions (CON2) in CYCLONE model.

5.2 Cycle completion

As it is discussed, a one-unit length (meter) of breakwater construction is completed when a one-unit length of core (equivalent to 8 trucks), filter (equivalent to 2 trucks) and armor (equivalent to 4 trucks) is placed. Since for placement efficiency of filter and armor, one joint backhoe is used, similar consolidate functions are preceded by placement tasks and filter placement is followed by a counter in CYCLONE model. For each cycle, the total production rate is obtained from equations 1 to 4, where parameter "P" corresponds to production rate (trucks per min) obtained from MicroCYCLONE outputs. One complete cycle corresponds to 4 cycles for core, 2 cycles for armor and 1 cycle for the filter.

$$[1]\quad \mathit{Filter\ production\ rate} = P \times 60 \times 1 \times 11 = P_f \quad \left(\frac{1}{hr}\right)$$

$$[2]\quad \mathit{Armor\ production\ rate} = P \times 60 \times 2 \times 10 = P_a \quad \left(\frac{1}{hr}\right)$$

$$[3]\quad \mathit{Core\ production\ rate} = P \times 60 \times 4 \times 12 = P_c \quad \left(\frac{1}{hr}\right)$$

$$[4]\quad P_{tot} = P_c + P_f + P_a \quad \left(\frac{1}{hr}\right)$$

At the meantime, EZstrobe simulation model was also developed to have more flexibility and output comparison.

6 MODEL IMPLEMENTATION AND VALIDATION

Since sufficient field data was valid for projects with 10 km hauling distance, these projects were tested for validation purpose. The following resources based on case study observations are assigned to the models: two loaders (Komatsu WA 470) to load trucks in the mine. One backhoe (Komatsu PC220) for core placement and one joint backhoe (Komatsu PC 400) for filter and armor. Six trucks (14 cubic meters) for hauling distance of 10 km from the mine to the site. One loader (Komatsu WA 470) for site loading. One truck (14 cubic meters) for site hauling. The cost for the main equipment was estimated regarding the recent rates (GSG, 2016) including: 68, 85, 68, and 100 $/hr for loader, truck, core backhoe, and armor-filter backhoe, respectively. Both models were ran based on initiated resources for 10-kilometer hauling distance projects. It should be noted that a limitation of EZstrobe regarding addressing probabilistic branching for transferring material to the storage area in the site is that only integer values are accepted. Therefore, it is assumed that all the transferred material dump is directly dumped in placement area. However, the results of MicroCYCLONE model (with and without probabilistic branching) indicate that the outputs obtained from both methods are the same for assigned resources in this study.

6.1 Production rate index

Usually, in simulation stage the productive time is estimated as 60 working minutes per hour. This assumption cannot be realistic since it does not reflect the impact of some qualitative factors. To adapt simulation results with the real practice, a production index of 50/60 is applied to simulation results (Zayed and Halpin 2004).

$$[5]\ \text{Final production rate} = production\ rate\ \times \frac{50}{60}$$

6.2 Validation factor

The outputs of equation 5 is compared to the observed production rate for validation purpose and robustness through a validation factor (VF) from Eq.6,

$$[6]\ Validation\ factor\ (VF) = \frac{Estimated\ production\ rate}{Collected\ production\ rate}$$

VF is obtained for each data point by dividing the estimated rate from simulation by the collected observations from field data. Based on case study reports, construction activities are assumed to be running 10 hours a day for 7 days a week. Table 3 presents the validation outputs for each section as well as the total production rate in each simulation method. As it is shown in this table, simulation outputs are validated which are close to one another.

Table 3: Validation outputs, and Comparison of results obtained from MicroCYCLONE and Ezstrobe.

Material	Production Rate (m^3/week)			Model Validation		Models Difference
	Web CYCLONE	EZstrobe	Field data	Web CYCLONE	EZstrobe	
Core	2150.4	2181.7	2591	0.83	0.84	1.4%
Filter	492.8	495.8	550	0.90	0.90	0.6%
Armor	896.0	892.5	788	1.14	1.13	0.4%
Total	3539.2	3570.0	3929	0.90	0.95	0.9%

In order to verify the task durations provided by experts, another model was developed by applying loading task durations provided by six experts in questionnaires instead of the recorded field data. For this purpose, the production rate outputs of the primary model were compared to the new one. The results indicate that outputs obtained from the two models are very close as presented in Table 4. Thus, it can be concluded that expert judgments for task durations in the model are validated.

Table 4: Data collection validation

Material	Loading task based on field observation		Loading task based on questionnaires			
	Task duration (Min.)	Productivity (m^3/h)	O (Min.)	A (Min.)	P (Min.)	Productivity (m^3/h)
Core	Uniform (low:2.31, high:7.51)	30.7	3.5	5.1	5.63	30.7
Filter	Exp. (mean:6.40)	7	2.85	6	6.15	7
Armor	Exp. (mean:9.50)	12.8	5.5	8.6	9	12.8
Total	-	50.6		-		50.6

7 SENSITIVITY ANALYSIS

Sensitivity analysis is performed considering different resource quantities for various hauling distances, i.e 10, 15 and 30 kilometers. From the production point of view, Figure 5 presents maximum total production rate for 10 kilometers hauling distance in case of using different truck numbers for a constant number of loaders. From this figure, the best alternative is using 2 loaders with 12 trucks for hauling since the corresponding production rate will not improve by adding more trucks. Table 5 illustrates the impact of changing number of joint filter/armor backhoes on production rate. As it can be seen, in case of increasing number of trucks from 7, the number of used joint backhoes will have an impact on system production. By increasing number of trucks and joint backhoes, enough trucks should be available for site loading (1 more).

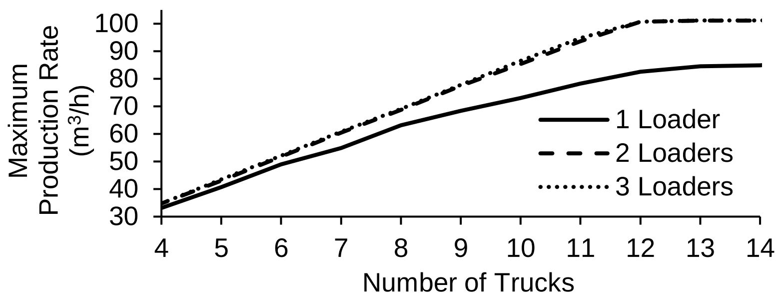


Figure 5: Max. production rate for different scenarios of 10 km hauling distance

Table 5: Changing production rate by using 1, or 2 joint backhoes in 10 km hauling distance

Truck Number	Production rate (m^3/h)					
	One Armor/Filter Placement Backhoe			Two Armor/Filter Placement Backhoes		
	1 Loader	2 Loaders	3 Loaders	1 Loader	2 Loaders	3 Loaders
4	33.2	34.8	34.8	33.2	34.8	34.8
5	41.5	43.1	43.5	41.5	43.1	43.5
6	49.0	51.0	50.6	48.6	51.7	52.1
7	50.6	50.6	50.6	54.9	60.0	60.4
8	50.6	50.6	50.6	62.8	68.7	69.1
9	50.6	50.6	50.6	68.7	77.4	77.8
10	50.6	50.6	50.6	73.1	85.3	86.5

Figure 6 presents minimum average cost per cubic meters in case of using different numbers of hauling trucks for a specific number of loaders and an optimum number for joint backhoes. According to this figure, the optimum alternative in terms of unit cost is using 12 trucks and 2 loaders. Also, the results indicate that dedicating number of resources as assigned in the case study will lead to an average cost of 19$/m3. However, by adding truck (6 for hauling plus 1 for site storage) and 1 backhoe, the cost will decrease to 16.5$/m3 while production rate increases by 100%. It means that this resource allocation is a more cost-effective solution unless lack of equipment, material or operational limitations do not allow managers to choose these alternatives.

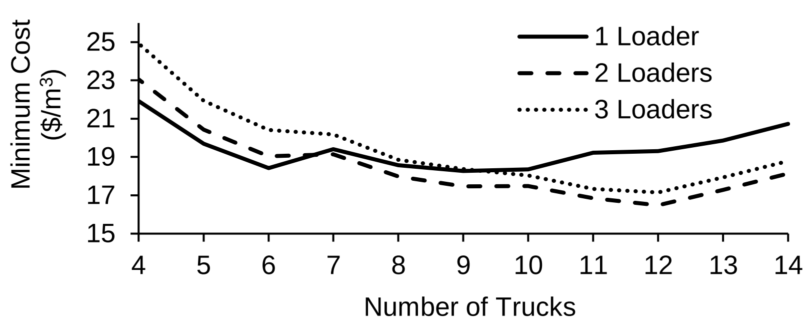


Figure 6: Minimum average cost for different scenarios of 10 km hauling distance

It may be expected that increasing number of placement backhoes and trucks changes production rate. However, in case of small and even moderate size breakwaters using 4 backhoes in a unique project is not applicable unless both breakwater arms are constructed in parallel. In this case, simulation analysis for one arm can be doubled and applied. As Figure 7 illustrates, results for different hauling distances follow similar patterns to ten-kilometer hauling distance (Figure 5). The results indicate that production rate is not improved by using more than 14 and 19 trucks for 15 and 30 km hauling distances, respectively. According to Figure 8, it is concluded that optimum alternatives in terms of cost and production rate for 10, 15 and 30 km hauling distances are a dedication of 12, 14 and 19 trucks, respectively. In addition, as it is expected, unit cost increases for these cases due to longer hauling distance, following a nonlinear trend.

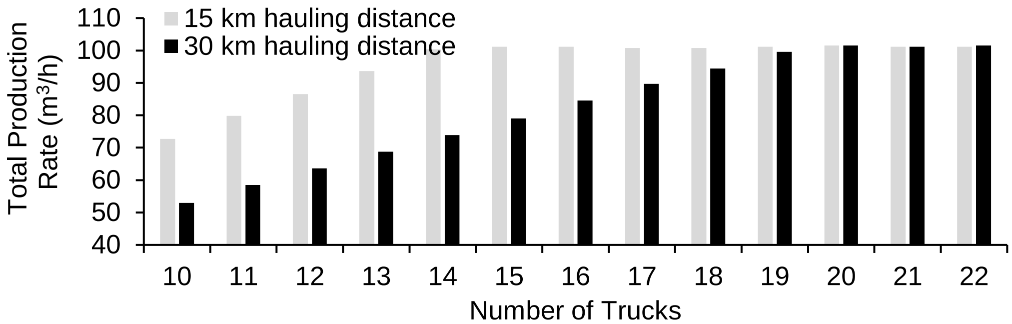


Figure 7: Total production rate using 2 loaders and 3 placement backhoes

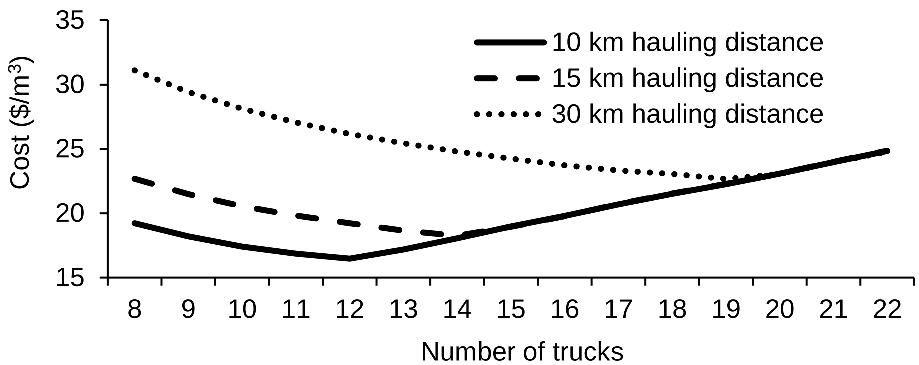


Figure 8: Average cost using 2 loaders and 3 placement backhoes

8 CONCLUSIONS

In this research construction of rubble-mound breakwaters was simulated with MicroCYCLONE and EZstrobe programs. In order to obtain accurate results, field production rate observations were collected from different projects with various hauling distances. Also, experts were asked to give their opinions regarding task durations and number of resources needed. The equipment cost was collected from current rates in practice. Both simulation results through MicroCYCLONE and EZstrobe methods were found acceptable. For validation purpose, the results of 10 km hauling distance were compared to the available field data. The results show that from the production point of view, for projects with 10 km hauling distance the best alternative for resource allocation is to use 2 loaders for loading, 12 trucks for hauling material from mine to the site and 3 backhoes for placement. Also for cost efficiency, it is recommended to use the same combination of resources. Sensitivity analysis proves that by adding more trucks (6+1) and 1 backhoe to the case study, more than 10% reduction in cost and 100% growth in production rate could be achieved. For projects with 15 km and 30 km hauling distances, the results indicate that it is more efficient to use 14 and 19 trucks, respectively. The results of this research can help the reader in simulation modeling. In addition, through this research project managers can estimate an optimum number of needed resources in terms of production rate and cost for construction of a typical rubble-mound breakwater.

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