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Simulation-based productivity analysis of dynamic compaction operations

Antonios Panas
Centre for Construction Innovation, National Technical University of Athens
cvapanas@mail.ntua.gr

John-Paris Pantouvakis
Centre for Construction Innovation, National Technical University of Athens
jpp@central.ntua.gr

Sergios Lambropoulos
Centre for Construction Innovation, National Technical University of Athens
laser@centeral.ntua.gr

Abstract

Dynamic compaction is a very common construction method for ground improvement. Despite its popularity, there is dearth of published research from a productivity point of view. As such, this paper analyses the activities that constitute the dynamic compaction paradigm and explores the main factors that affect the on-site productivity. A simulation model is created based on the STROBOSCOPE simulation language and key production parameters are identified. Field data are collected and the created datasets are statistically elaborated to determine the input of the simulation experiment. The model's output is compared to actual results for verification and validation purposes. As such, baseline reference estimates of expected productivity are created and their robustness is tested in an actual project setting. The main inferences emerging from the study indicate that the method statement plays an important role in determining the model's structure. In addition, the selected grid spacing of a given area, as well as the number of hits has been found to significantly affect dynamic compaction operations' productivity.

Keywords

Dynamic compaction, Productivity, Simulation

1. Introduction

Dynamic compaction is a soil improvement method that has been extensively used due to its cost-effectiveness, simplicity and considerable depth it affects (Feng *et al.*, 2010). It is a ground improvement method which was first popularized by the French Firm Menard Techniques in 1975 (Miao *et al.*, 2006). The basic process comprises the repeated dropping of a weight onto the ground surface as a direct way to treat poor ground, such as natural soils or a variety of loose partially saturated fills (BRE, 2003; Feng *et al.*, 2011). In recent decades, dynamic compaction has exhibited its versatility in different types of civil engineering projects, including building structures, container terminals, highways, airports, dockyards and harbors (Feng *et al.*, 2010). However, despite its popularity in soil improvement, dynamic compaction is an operation that has not been examined in detail in published literature from a productivity estimation viewpoint. In addition, the Federal Highway Administration in the U.S.A. highlights that dynamic compaction's productivity estimation is an essential element in the design stage of a project, since it serves as a yardstick against which alternate site improvement techniques are examined (Federal Highway Administration, 2005). Hence, the objective of this paper is to study the operations involved in dynamic compaction under the prism of a specific large-scale infrastructure project related to the construction of a container terminal.

The structure of the paper is as follows: First, background information on pertinent research on construction simulation studies is going to be provided, followed by a concise description of the selected simulation language and software. Then, the research methodology is going to be delineated and, subsequently, the model set-up process, including the definition of the workflow and the distribution fitting procedure will be presented. The model's verification, analysis and validation will be described and, finally, the main emerging inferences will conclude the study.

2. Background

Construction operations call for decisions to be made that should be based upon credible information (Pantouvakis and Panas, 2013). Simulation models are able to assist the decision-making process by highlighting the inherent characteristics of the modeled system (AbouRizk *et al.*, 2011; Panas and Pantouvakis, 2013). Using computer simulation tools, models can be built that represent the overall logic of various activities required to construction a facility, the resources involved in carrying out the work (e.g. crews, equipment, management) and the environment under which the project is being built (e.g. weather, ground conditions, labour pools, market situation) (AbouRizk, 2010). Discrete-event simulation has been extensively used for the analysis of construction systems (Martinez, 2010) and covers a wide spectrum of projects (large infrastructure projects, machine-intensive, labour-intensive operations).

In this study, the advanced simulation software products STROBOSCOPE and EZStrobe were employed. The state and resource based simulation of construction processes (STROBOSCOPE) simulation system is an advanced general purpose simulation tool that can determine the state of the simulation and the characteristics of the resources involved in an operation in a dynamic fashion (Ioannou and Martinez, 1999). The EZStrobe simulation platform was developed, so as to enable the use of the STROBOSCOPE simulation language in a more simple and graphical form (Martinez, 2001). EZStrobe is based on Activity Cycle Diagrams (ACD) and implements the three-phase activity-scanning paradigm. The reader is referred to Martinez (2001) for a detailed description of the modeling elements used for the EZstrobe system.

3. Research Methodology

The research methodology is depicted in Figure 1 below. First, the model is being set up by the use of the preferred simulation language (e.g. STROBOSCOPE). The model set up depends on the method statement which determines the type and sequence of the activities involved in the operation under study. Then, the data collection process initiates which comprises direct observation of construction activities combined with experts input (e.g. interview with project manager) to improve the robustness of the created data sets. The possible distribution functions can be selected along with their parameters based on summary statistics (e.g. quantile summaries, box plots) (Martinez, 2010). The goodness of fit for the selected distribution is being evaluated by the creation of specific graphs (e.g. Q-Q or P-P plots) combined with statistical checks (e.g. Chi-square, Kolmogorov-Smirnov, Anderson-Darling) (AbouRizk and Halpin, 1990; Maio et al., 2000). An iterative process is being initiated until the proper distribution has been defined. After the statistical checks have been successful, it is assured that the model is verified, namely that it actually represents what the developer or engineer had in mind (Shi, 2002). In the case of failure to verify, the model set-up process must be re-visited to adjust accordingly. Upon verification of the model, simulation runs can be executed. First, pilot runs are executed to define the model's behavior. If satisfied, the number of independent replications is determined and the simulation experiment is designed. The results are compared to the actual data and it is evaluated to what extent the abstract model corresponds to the actual situation on-site, i.e. model validation. If the validation results are not satisfactory, new data must be provided to the model so as to improve its accuracy. Sensitivity analysis is performed to optimize the model's performance under variation of the critical model parameters. Sometimes, the decision making process requires the examination of alternative scenarios (e.g. different construction methods and techniques). In this case, alterations in the model set-up must be induced, so as to represent the variations in the operational setting. A detailed description of the methodological framework's implementation in the analysis of the dynamic construction operations is presented in the following sections.

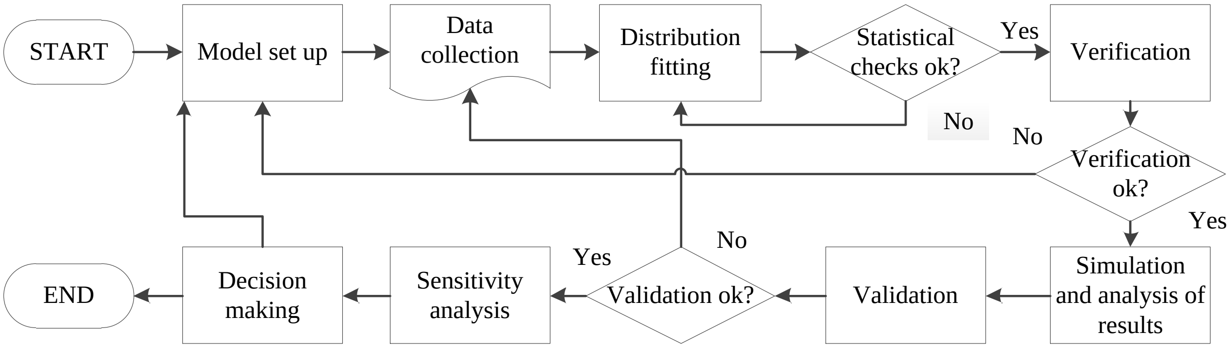

Figure 1: Research Framework

4. Model Development

4.1 Definition of workflow

The main objective of dynamic compaction is the increase in the bearing capacity and the reduction in the settlement under repeating the applied loading of a tamper weight attached at a crawler crane. There are four steps that have to be applied for the specification of a dynamic compaction operation, as follows:

Step 1 – Selection of tamper and drop height for required depth of improvement: The weight ranges between 10-40 tons and the drop height varies from a minimum of 10m to a maximum of 30m (Miao et al., 2006). The depth of influence is proportional to the square root of the tamper weight times the drop height (Terashi and Juran, 2000; Federal Highway Administration, 2005) (see Equation 1):

$$D = n*(W*H)^{0.5} \text{ (Eq. 1)}$$

where: D = depth of improvement (m); W = mass of tamper (Mg); H = drop height (m); and n = empirical coefficient that is less than 1.0.

The depth of improvement is determined by the design study and both the tamper mass, as well as the drop height can be empirically determined by the use of special nomographs.

Step 2 – Project area to densify: For a known average energy value that has to be applied at ground surface the designer determines the geometrical characteristics (width and length) of the area that needs improvement. For level sites the engineer should apply a grid spacing throughout the area in need of improvement plus a distance beyond the project boundaries equal to the depth of improvement. If slope stability is a concern, then improvement over a wider plan area may be required.

Step 3 – Grid spacing and drops: The grid spacing ranges from 1.5 to 2.5 the diameter of the tamper. Then, Eq. 2 is used to determine the number of drops and passes. Generally, 7 to 15 drops are made at each grid point. If the calculations indicate significantly more than 15 or less than 7 drops, then the grid spacing should be adjusted.

$$AE = N*W*H*P \,/\, (\text{grid spacing})^2 \quad \text{(Eq. 2)}$$

where: AE = applied energy; N = number of drops; P = number of passes; W = mass of tamper; and H = drop height.

Step 4 – Multiple passes: The number of passes over a specific area depends on the soil properties and the predicted crater depth of the ground heave that is going to be formed as a result of the dynamic compaction operation. The crater depth should be limited to the height of the tamper plus 0.30m. Normally, one or two passes should suffice. On any case, if more than one pass is required to apply the energy, then the number of drops per pass decreases proportionally. In other words, the product of number of drops and number of passes must remain the same. For example, if 12 drops are required at each grid point location (as per Eq. 2), but only 6 drops can be completed before the crater depth becomes excessive or excessive water pressure develops, then two passes of 6 drops per pass will be required.

In view of the aforementioned, the main construction tasks that have to be completed, in order for the dynamic compaction operation to take place are depicted in Figure 2 below. In principle, the process usually requires the deployment of a crawler crane, which bears the tamper weight, and a truck-grader system which supplies the required material for backfilling the craters. The dynamic compaction is executed on a specified grid and comprises three phases: Phase A regards the drop of the tamper weight in an area that is square-shaped and normally extends within the range of a 6mX6m to 8mX8m canvas. In Phase A the crane hits the four angles of the fictional square, as well as its center. After completing a given area, Phase B initiates where the crane hits the middle points of each side on the previously defined square. Finally, Phase C (or “ironing” phase) regards the hitting of the square area in a tighter grid which intends to increase the density of the dynamic compaction. As shown in Figure 2, by the completion of each phase, a truck supplies aggregate material which is subsequently used to fill in the craters that have been created by the use of a grader. It should be noted though, that this task is sub-critical to the process, since it has been observed that proper planning allows for a continuous flow of backfill material at the site. As a result, the process depicted in the middle picture of Figure 2 has been omitted in the developed simulation model, as will be explained in the next paragraph.

Figure 2: Dynamic compaction operations

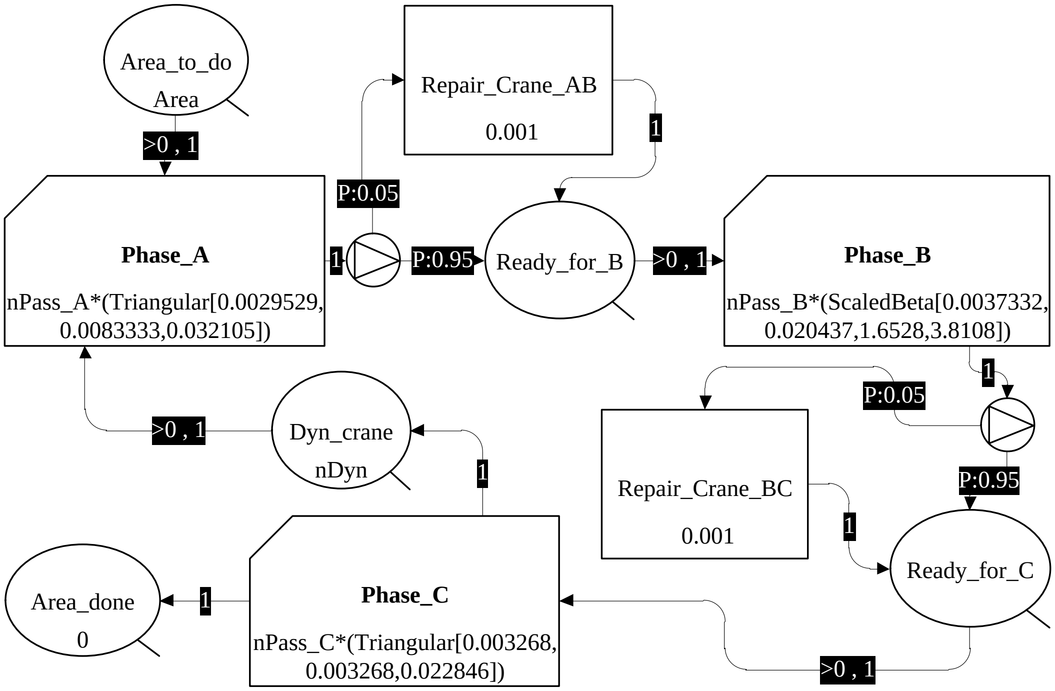

Figure 3: Dynamic compaction EZStrobe simulation model

The developed simulation model is depicted in Figure 3. First, the area (in m^2) that is going to be dynamically compacted is specified (Area_to_do) along with the number (nDyn) of cranes (Dyn_crane) to be deployed. After the definition of the operation's resources, Phase A initiates. The duration of the Phase A task is multiplied by the number of required passes (nPass_A) to complete the grid area. Before the initiation of Phase B, a probabilistic routing has been created, which denotes that there is a 5% probability of a delay in the operation due to crane downtime. This delay may be due to the equipment breakdown, need for non-scheduled maintenance etc. Upon the completion of the repair, Phase B initiates in exactly the same manner as Phase A. Phase B is followed by Phase C, as described in the previous paragraph. Once the dynamic compaction operation has started with Phase A, the crawler crane becomes unavailable for any other activity. It becomes available after the completion of Phase C. This modeling strategy reflects an operational scenario that is often met in real life projects. That is, the construction manager prefers to completely process an area through all three phases of the dynamic compaction before moving on to a new segment. However, in case a different operational setting is to be implemented (e.g. hitting an area for Phase A and then moving to another area to hit Phase C), then the simulation model should be modified. On any case, although it is a rather simplified and straightforward model, it provides useful and credible results, as will be presented in the next section.

4.2 Data collection and distribution fitting

Productivity field data expressed in workhours/activity's output (e.g. whs/m^2) have been collected for every sub-task depicted in Figure 3. A 15 ton tamper weight is used for the dynamic compaction of granular soil and one pass is implemented in all phases. Each grid point is hit 8 times from a height of 27m. The direct observation technique complemented by time-lapse video was deployed to record the data for a period of 10 months. The recorded durations for each activity were fitted to a pre-defined probability distribution (Beta, Erlang, Exponential, Gamma, Normal, Triangular and Uniform) based on the analysis of the collected data. The BestFit distribution fitting add-on of the @RISK (Palisade, 2013) software package has been used for the distribution fitting process. Indicatively, the distribution fitting process for the dynamic compaction activity of Phase B will be presented next. The selection of the best fitted continuous distribution function and the determination of its parameters were based on quantile summaries. Additionally, the chi square, Kolmogorov-Smirnov and Anderson-Darling tests at a 90% significance level were also taken into account. Ultimately, the beta distribution was found to be satisfactory for representing the Phase B of the dynamic compaction activity. Figures 4 presents a comparison between the input data and the fitted beta cumulative distribution function. In a similar manner, the triangular distribution was selected for Phase A and Phase C respectively. The statistical parameters of the selected distributions are depicted in Figure 3.

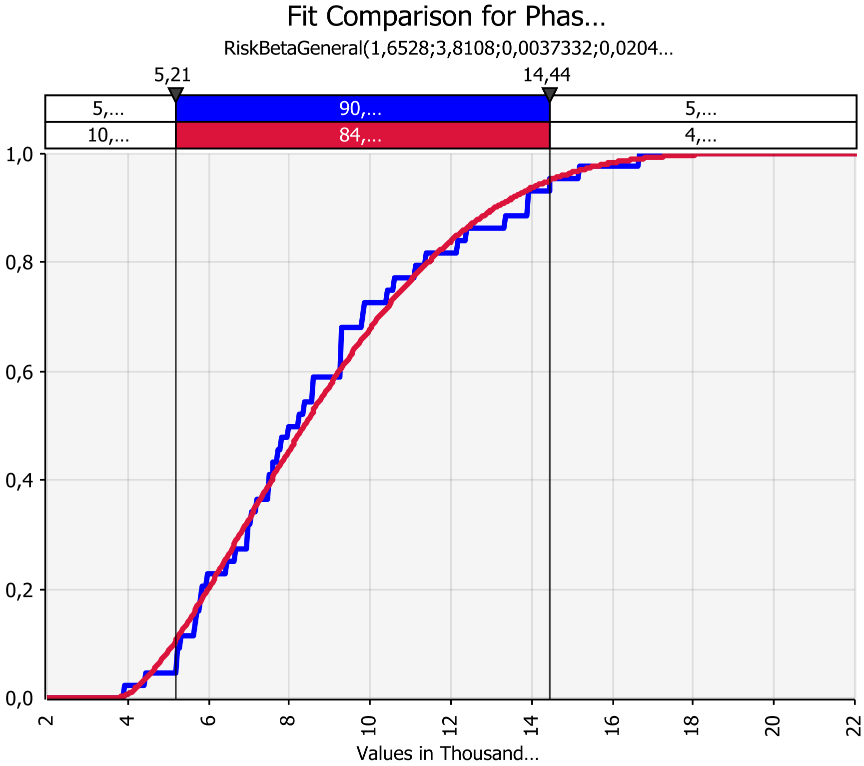

Figure 4: Dynamic compaction Phase B Cumulative Density Function

4. Verification, analysis and validation

The verification process has been threefold, by implementing the three white-box methods proposed by Shi (2002). First, the model set-up was verified by consultation with the project director and the site engineer. Then, the program per se was tested by confirming the sequence of the activities' execution. EZStrobe's inherent animation features were used to visualize the simulation progress and ensure that the chronological order of the activities was correct. A deterministic pilot run of the model was also executed to check the starting activities and their conditions, while the produced simulation report was utilized to control the logic behind the initiation conditions of the model's resources and activities. The summary statistics of each pilot run coincided with the actual measurements on site (mean durations, achieved productivity). Finally, EZStrobe's generated trace output served as a yardstick against which the resources flow between the activities was again verified. The simulation results were based on 30 independent replications yielding an average productivity of 0.033 whs/m^2, which was slightly overestimated in relation to the actual productivity value of 0.031 (+6,45%), as shown in Table 1. A similar trend is presented for the duration of the project, which denotes a good convergence of the simulation analysis. In total, after extensive consultation with project experts the model's face validity has been deemed to be at a satisfactory level. The sensitivity analysis relates to varying the number of the crawler crane. As expected, productivity is directly proportional to the number of cranes, since doubling the number of deployed cranes leads to an equal increase in productivity. It should be noted that some critical project parameters have been assumed to be constant for the study of the operation. For example, the sub soil thickness is relatively stable, whereas the induced settlements result in a satisfactory compaction of the sub-layer, since the process of measuring and evaluating the geotechnical characteristics of the soil after the compaction has been excluded from the research scope. In addition, the energy absorbing layer is uniformly structured and there is no need for adding a stabilizing surface material of granular soil to form a working mat. In that view, the simulation experiment findings should be evaluated within the framework of the previously defined operational setting. The external conditions must be taken into account in detail and explicitly documented if not possible to be incorporated in the model's scope.

Table 1: Comparison of actual and simulation results

Estimated parameters	Simulation results		Actual Data
	Average	St. Dev.	
Total duration (h)	1,000.26	1.29	921.63
Productivity (h/m^2)	0.033	0.00004	0.031

5. Conclusions

The objective of this paper was the development and validation of a credible simulation model for dynamic compaction operations. The implementation of the developed methodological framework was successful and the achieved accuracy of the simulation model was accepted by the project executives. The importance of the external conditions, and the contextual information underpinning the recorded field data was highlighted, since failure to acknowledge their implications for the analysis can result in adverse effects for the model's validity. In total, the developed model is believed to be a practical tool for both academia and practitioners and possible extensions to include the examination of alternative construction methods and the inclusion of cost factors could be potential topics for further elaboration in the future.

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