Abstract

The construction of modern high-speed motorways has increased over the last decade all over the world. However, the financial crisis led many financial institutions worldwide to impose stricter credit limitations and seek to finance only high-profit investments. As a result, the financing of transport projects was made even more difficult. At the same time, accurate cost estimates at the preliminary stages of a project are essential to all the major project stakeholders since they are necessary for the budget determination, allocation and monitoring, the comparison of alternative projects and technical solutions and finally, the selection of the projects to be implemented. However, the required degree of accuracy is very difficult to be achieved at the preliminary stages due to the limited extent of available information.

This paper presents a preliminary predesign cost estimate model for culverts, i.e. conduits for the passage of surface drainage water under the motorway. Although culverts present low construction cost when compared individually to bridges, tunnels or large retaining walls, their total number along a motorway renders their total construction cost significant. The model utilizes a properly developed database derived from actual construction projects to produce accurate quantity estimates by means of the statistical technique of linear regression. Following the estimation of quantities, proper material unit prices can be applied for quick and reliable cost estimates to be provided. The proposed model only requires limited input and thus, can be used in the early project stages, offering valuable contribution towards the accurate culverts' cost prediction in motorway projects.

Keywords: Cost estimation; Cost model; Culverts; Regression analysis

1. Introduction

The European Union (EU) considers transport infrastructure as vital to the European economy, since freight and passenger transport are expected to grow by 80% and 50% respectively by 2050 [1]. The new EU infrastructure policy aims at putting in place a powerful transport network across 28 member states that will streamline the free flow of goods and services and promote growth and competitiveness. At the same time, it triples EU financing for transport for the period 2014–2020 to €26 billion. Investments in transport infrastructure also contribute to the goal of the reduction of greenhouse gas emissions in transport by 60% by 2050.

China, one of the world’s biggest economies, also presents accelerating development in transport infrastructure. According to data available for 2012 [2], investment in fixed assets reached 1,713 billion yuan with an annual 6.60% increase, while the length of highway in operation amounted to 4.2 million km with an annual 3.20% increase.
According to the 12th five-year development plan for integrated transportation system, the total length of highway in operation will reach 4.5 million Km by the end of 2015. Apart from the EU and China, considerable progress has been made by many landlocked developing countries (LLDCs), such as Kazakhstan and Kyrgyzstan, in infrastructure development [3]. The proportion of roads that are paved in LLDCs increased from 28% to 37% in 2011. In South America [3], the Initiative for the Integration of Regional Infrastructure in South America had 474 transportation projects in 2012, with highway projects accounting for the largest proportion (47.50%).

Transport infrastructure projects' successful construction is mainly determined by two factors: time and money. These projects must be completed within the projected time and budget constraints. Cost estimates prepared during the preliminary predesign stages are used to determine the available project budget and eventually form the basis for which the actual construction cost will be compared against. As a result, it is essential to reach preliminary cost estimates that present the highest possible accuracy, in spite of the fact that project design is conceptual and limited project information is available.

Culverts are generally conduits for the passage of surface drainage water under a highway. They are usually used to drain ditches or small streams. Most culverts built in Greece are made of reinforced cast-in-place concrete in box shapes. Precast sections are rarely used. Culverts' design and capacity is mostly dependent upon the water surface profile and the street drainage. Culverts present a minimum slope required to achieve the necessary water velocity. Concerning their alignment, they are usually aligned with the natural channel, while passing beneath the motorway normal to its centerline or at an angle. Wingwalls in the culverts' ending sections are designed to prevent the motorway's embankments from collapsing. Culverts present low construction cost when compared to large-scale structures such as tunnels and bridges. However, every motorway includes a large number of them and as a result, their total construction cost becomes significant for the project.

This paper presents a preliminary cost estimate model for culverts that utilizes a database derived from actual construction projects. The statistical analysis of the collected construction and design data with the linear regression technique led to quantity prediction models for the culverts' concrete and reinforcing steel. Following the estimation of quantities, proper material unit prices can be applied for quick and reliable cost estimates. The culverts' remaining cost elements can be estimated with the proposed total cost breakdown. The cost estimate model only requires limited input and thus, can be used in the early project stages.

2. Literature survey

A reliable preliminary engineering during the pre-construction stage is the core foundation for managing roadway construction projects in terms of fulfilling the three basic components of scope, schedule, and cost [4]. In this context, a number of research publications devoted to the development of preliminary cost estimation systems for highway projects as a whole can be found in the literature [5,6,7]. However, regarding culverts in particular, most available publications originate from public clients, such as state transportation agencies / departments and are usually based on bids from projects awarded. For example, Idaho's Transportation Department [8] provides cost per square foot indices for the preliminary estimate of total structure cost. These values apply to new cast-in-place box culverts, as well as to the widening of existing projects. Colorado's Urban Drainage and Flood Control District [9] developed a cost estimating tool for master planning projects. The user selects one of the available standard culvert box sizes and the software produces material unit and cost estimates based on standard specifications, as well as cost estimates for wingwalls. Furthermore, several public clients have published design manuals for culverts [10,11]. These manuals provide useful insight to engineers on the design criteria, policies and limitations and in several cases, describe procedures for the culverts' hydraulic design. On the other hand, they rarely include specific estimates for the volume of concrete and the weight of reinforcing steel. Arizona Department of Transportation [12] is one example of transportation agencies that publishes drawings with details on concrete dimensions and reinforcing layout.

In addition to publications originating from the state transportation agencies, Yassin [13] presented a procedure for the economic sizing of box culverts and formulated a set of equations for the cost estimation of 13 different box culvert sizes. The prediction models referred to culverts of one vent and did not cover the cost of wingwalls. Essam [14] considered specific assumptions for the soil bearing capacity of soil, the live loads, the soil properties and the reinforced concrete and steel strength and developed a program for culvert structural design that estimated the
quantities of reinforced concrete for 72 different single-vent layouts. He estimated the cost using market prices for the material quantities and performed multiple regression analysis to relate the culvert cost to different design factors.

3. Proposed Model for Culverts Conceptual Cost Estimate

The cost estimate model presented herein does not produce direct cost values of cost per surface area. These values depend on each country’s related factors and consequently, require careful parameter adjustment before being applied to other countries. The procedure of infrastructure projects’ construction (procurement method, design and construction management), the financial condition and capacity of the construction companies, as well as financial factors (economic growth, inflation rate, financing conditions) are typical examples of these parameters.

The proposed conceptual cost estimate model for box-shaped cast-in-place concrete culverts involves firstly, prediction of the most significant material quantities and secondly, estimation of the construction cost. The processing with statistical techniques of data collected from recently constructed structures, leads to prediction models for the quantities of concrete and reinforcing steel. The construction cost is then derived by multiplying the estimated quantities with the unit prices specified by the user. The cost of the remaining construction activities is estimated with the proposed total cost breakdown derived from actual structures.

4. Database development

Material quantities and design parameters were collected from recently constructed structures as part of the Egnatia Motorway and the Motorway of Western Greece named "Ionia Odos". The data were collected from the final bill-of-quantities tables formed after the structures' construction and not from the initial design studies, in order to record as-built information that includes all design changes during the construction phase.

The collected data from 104 culverts were stored in a database. The material quantities for all construction activities were recorded. These activities include the unreinforced concrete for smoothing the ground, the concrete and steel reinforcement for the culvert, earthworks (excavations, backfilling and soil enhancement), concrete surfaces finishing (anti-pollution coating, water-proofing membranes and asphaltic coatings), joints’ sealing and drainage (pipes, geotextiles, filling material). The database also includes the fundamental design parameters for each structure and in particular the culvert's net width and height, the seismic zone according to the Greek standard for earthquake resistant structures and the overburden height of ground.

The structures included in the database were designed with the German DIN codes. The Greek standard for earthquake resistant structures was used for earthquake loading. The culverts are made of reinforced cast-in-situ concrete and have rectangular box shapes, with constant cross-section throughout their length. They include a bottom slab, two side walls and a top slab, as well as wingwalls in the structures' ending sections. The culverts' net width ranges from 2.00 to 8.00m, the net height ranges from 1.50 to 4.15m, while the overburden height of ground ranges from 0.50 to 27.00m. The structures’ total length fluctuates between 8.00 and 126.90m.

5. Cost Breakdown

The activities involved in the construction of a culvert were subdivided in three categories: earthworks, structure and miscellaneous. Earthworks include excavations, backfilling and the soil enhancement layer. The structure category refers to the construction of the main structure (i.e. the box) with the wingwalls, while the miscellaneous category includes all remaining cost items. The material quantities for all construction activities recorded in the database were multiplied with the official unit prices determined by the Greek Ministry of Public Works in order to determine the total cost for each activity.

Table 1 presents for all culverts the three cost subcategories as percentages of total construction cost. The structure represents the most important cost item accounting in average for 70.93% of the total cost. Earthworks and miscellaneous activities represent in average 18.23% and 10.84% respectively of the total cost. All cost categories present low variance.
Table 1. Culverts' sub-costs as percentages of total cost

<table>
<thead>
<tr>
<th></th>
<th>Earthworks</th>
<th>Structure</th>
<th>Miscellaneous</th>
</tr>
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<tbody>
<tr>
<td>MIN</td>
<td>13.15%</td>
<td>69.56%</td>
<td>9.61%</td>
</tr>
<tr>
<td>MAX</td>
<td>20.38%</td>
<td>74.60%</td>
<td>12.86%</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>18.23%</td>
<td>70.93%</td>
<td>10.84%</td>
</tr>
<tr>
<td>STD</td>
<td>3.20%</td>
<td>1.96%</td>
<td>1.31%</td>
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</table>

6. Material prediction model development

The prediction models for the quantities of concrete and reinforcing steel should take into account the parameters with the most substantial impact on the design. Culverts' design is generally affected by numerous variables related to the structure and the specific site. In order to select the most influential parameters, several interviews were conducted with civil engineers with significant experience in bridge design, structural experts and academics. These interviews highlighted the culverts' design process. First, the designer considers the hydraulic conditions of the stream (e.g. water profiles, flood data) and the motorway alignment, in order to calculate the water discharge and velocity and the critical depth and finally determine the necessary clear width and height of the culvert. The dimensions and steel reinforcement of the culvert are then calculated based on the site's seismic conditions and the overburden height of ground. Wingwalls are typically suspended from the side walls of the culvert. Their design depends on site-related factors, such as the ground morphology, as well as on the height of the culvert.

To sum up, the experts identified the net height ($h_{net}$), the net width ($b_{net}$), the height of the overburden ($h_{over}$) and the seismic conditions as the parameters with the most substantial impact on the design of the culverts' box. Hydraulic conditions are included in the aforementioned parameters, as they are used for the calculation of the culverts' net dimensions. The culverts database does not currently include satisfactory data samples for all seismic zones of the Greek earthquake resistant structures standard. The largest part of the sample has been designed with similar seismic parameters. Consequently, the earthquake conditions are excluded from the proposed material prediction models. The net height and width and the overburden height are selected as independent variables in the statistical analysis, while the volume of concrete ($V_c$) and the weight of reinforcement steel ($B_s$) are the two dependent variables. Since the culverts' cross-section remains constant throughout the structures' length, the quantities of concrete and reinforcing steel of the box are expressed in terms of one meter culvert length.

6.1. Statistical analysis

The examined regression model is linear, of the following form:

$$Y = a + b_0 \times h_{net} + b_1 \times h_{net} + b_2 \times h_{over}$$  \hspace{1cm} (1)

where $Y$ stands for the dependent variables ($V_c$ and $B_s$) and $h_{net}$, $b_{net}$ and $h_{over}$ are expressed in meters.

The methodology followed for the regression analysis includes statistical hypothesis tests to check the significance of the overall models and the independent variables, combined with a rationality check of the regression coefficients. The adjusted coefficient of determination ($R^2$) provides a measure of the total variability explained by the model. The F-value checks the hypothesis that the regression model does not explain the dependent variables and as a result, its coefficient of determination is zero. The F-significance denotes the probability that this hypothesis is true. Statistical hypothesis test is additionally performed to check the significance of the independent variables. The p-values express the probability that each independent variable has no effect on the dependent variable and its regression coefficient is zero. Finally, the models' regression coefficients are checked for theoretical correctness.

Table 2 presents the regression statistics for the two models and in particular, the $R^2$, the results of the F-test (F-significance, F-value) and the p-values for the independent variables. The following equations provide predesign...
estimates for the volume of concrete and the weight of reinforcing steel for concrete cast-in-situ single box-shaped culverts.

\[ V_c = -4.083 + 2.459 \times b_{net} + 0.673 \times h_{net} + 0.216 \times h_{over} \]  \( \text{m}^3 \text{ per 1m. culvert length} \)  \( \text{(2)} \)

\[ B_s = -562.023 + 284.674 \times b_{net} + 98.080 \times h_{net} + 20.913 \times h_{over} \]  \( \text{kg per 1m. culvert length} \)  \( \text{(3)} \)

<table>
<thead>
<tr>
<th>Table 2. Regression statistics</th>
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<tr>
<td>( V_c ) &amp; ( B_s )</td>
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<tr>
<td>R²</td>
</tr>
<tr>
<td>F-value</td>
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<tr>
<td>F-significance</td>
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<tr>
<td>p-value b_{net}</td>
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<td>p-value h_{net}</td>
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<td>p-value h_{over}</td>
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The volume of concrete and the weight of steel reinforcement per one meter culvert length estimated with equations 2 and 3 respectively include the box of the culvert, as well as the wingwalls.

6.2. Testing the linear regression assumptions

The R² values for the two regression models exceed 84% and indicate that the proposed models explain the most substantial part of the total variability. The F-significance and the p-values verify that the regression models and the independent variables respectively are statistically significant at a 5% significance level. The regression coefficients of equations 2 and 3 are positive and consequently, theoretically correct.

Multicollinearity is the situation where the independent variables of regression modeling are highly intercorrelated. High levels of multicollinearity may lead to large variances and standard error of the ordinary least squares estimators (regression coefficients), wider confidence intervals, wrong signs for regression coefficients, deceptive results in terms of statistical significance and increasing difficulty in assessing the individual contribution of each independent variable to the overall model fit [15]. The potential existence of multicollinearity was initially investigated with the Pearson product-moment correlation coefficients. The variance inflation factor (VIF) was also explored as additional indicator of multicollinearity. Auxiliary regressions in which each independent variable was regressed on the other independent variables were performed, in order to determine the relevant coefficients of determination and finally calculate the VIF. The Pearson product-moment correlation coefficients among the dependent and independent variables, as well as the VIFs are presented in Table 3. The values of VIF are significantly smaller than the suggested by Chatterjee and Price [16] value of 10, while the pairwise correlations among explanatory variables are relatively low, indicating that multicollinearity did not cause problem for the models.

The assumptions of the correct application of the regression methodology require the error term of the model to be normally distributed, have a mean value of zero and a constant variance [15]. The pattern of several types of residual plots was investigated and indicated the normality of the error terms. The assumption of normality was also tested with the use of the Jarque-Bera test [17]. The skewness and kurtosis of the two residual samples were initially determined. The test statistic for both samples was calculated. It did not exceed the critical chi-square value of 5.99 for two degrees of freedom and 5% significance level and verified the normality assumption of the error terms. Furthermore, the mean value of the residuals approached the value of zero. The constant variance of the error terms (i.e. homoscedasticity) was tested with White's general heteroscedasticity test [18]. The test's auxiliary regression was performed and the test statistic that equals the product of the sample size with the R² of the auxiliary regression
was calculated. The probability of obtaining the chi-square value of the test statistic exceeded the selected level of statistical significance (5%) in both cases and led us to accept the null hypothesis of no heteroscedasticity.

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<thead>
<tr>
<th></th>
<th>Vc</th>
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<th>hover</th>
<th>hnet</th>
<th>VIF</th>
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<tbody>
<tr>
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<td>1.000</td>
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<td>1.301</td>
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<td>-0.123</td>
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<tr>
<td>VIF</td>
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<td>1.565</td>
<td>0.512</td>
<td>1.738</td>
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7. Conclusions

The proposed preliminary cost estimate model for culverts includes first estimation of the quantities of concrete and reinforcing steel of the structure and then prediction of the relevant costs by applying the proper unit prices. Actual construction data gathered from recent projects were statistically analyzed with linear regression in order to derive the material quantity prediction models. These models require as inputs the culverts' net width and height, as well as the overburden height, data available during the early design project phases. The unit prices for concrete and reinforcing steel are specified by the user and enable the proposed cost model to produce different estimates according to the user. The proposed culverts' total cost breakdown is used to derive the remaining cost elements (earthworks and miscellaneous). The cost estimate model is based on actual as-built data and produces reliable results. It can be used in the early project stages and constitutes a valuable tool for the projects' stakeholders.

References