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Preliminary cost estimate model for culverts

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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 degree of accuracy required 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 individual culverts present low construction cost when compared to bridges, tunnels or large retaining walls, their total number along a motorway is significant and thus, their total construction cost is also substantial. The proposed 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 are 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.

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1. Introduction

Transport infrastructure is fundamental to modern living, making it possible for people to travel for work and leisure, and for businesses to move goods and materials. As the backbone of a country's transport system, roads keep the population connected and the economy flowing and constitute a critical element of the social, economic and environmental wellbeing. In the European Union (EU), freight and passenger transport are expected to grow by 80% and 50% respectively by 2050 [1]. In this context, the new EU infrastructure policy aims at putting in place a powerful transport network across the 28 member states to streamline the free flow of goods and services and promote growth and competitiveness. With this in view, the EU tripled the financing for transport for the period 2014–2020 to €26 billion.

Furthermore, 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 a length of 4.5 million km by the end of 2015. Apart from the EU and China, considerable progress has been made in infrastructure development by many landlocked developing countries (LLDCs), such as Kazakhstan and Kyrgyzstan [3]. The proportion of paved roads in LLDCs increased from 28% to 37% in 2011. Moreover, in South America, the Initiative for the Integration of Regional Infrastructure had 474 transportation projects in 2012, with highway projects accounting for the largest proportion (47.50%) [3].

The successful construction of transport infrastructure projects is mainly determined by two factors: timely completion and adherence to budget. However, the cost estimates which determine the available project budget and thus form the cost baseline for the actual construction cost to be compared against, are prepared during the preliminary stage of pre-design. Therefore, it is a great challenge to reach preliminary cost estimates with high accuracy despite the project design being at a conceptual stage and the available project information being rather limited.

Culverts are generally conduits for the passage of surface drainage water under a highway, also usually used to drain ditches or small streams. Culverts' design and capacity are mostly dependent upon the water surface profile and the street drainage. Culverts present a minimum slope required to achieve the necessary water velocity and 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. Most culverts are made of reinforced cast-in-place concrete in box shapes; precast sections are rarely used. Culverts present low construction cost when individually compared to large-scale structures such as tunnels and bridges. However, as every motorway includes a large number of them, 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 collected design and construction data were statistically analyzed with the linear regression technique leading to equations enabling the prediction of the concrete and reinforcing steel quantities from the culvert's net width and height, as well as from the overburden height. Following the estimation of quantities, proper material unit prices can be applied for quick and reliable cost estimates to be derived. Furthermore, the total cost breakdown in different construction activities, as this emanates from the available construction data, can be further used to estimate the culverts' remaining cost elements. The cost estimate model only requires limited input and thus, can be used in the early project stages.

2. Literature survey

A reliable estimate of preliminary engineering cost during the pre-construction stage is the core foundation for successfully delivering motorway construction projects in terms of their scope, schedule and cost [4]. In this context,

a number of research publications devoted to the development of preliminary cost estimation systems for motorway 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, 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.

According to the Association for the Advancement of Cost Engineering's cost estimate classification system [15], the cost estimates used for project screening, determination of feasibility, concept evaluation and preliminary budget approval (class 4) are typically derived by parametric and modeling techniques with the use of limited information. A parametric cost-estimating model includes a relationship which derives the dependent variable, i.e. the cost, from the independent variables, i.e. the cost-influencing factors. Material quantities constitute usual cost-influencing factors in most construction projects. Regression analysis represents one of the most widely used methods for parametric cost estimation during early project stages. Despite its widely analyzed drawbacks like the requirement of a defined mathematical form to fit the available historical data and the difficulty in accounting for the large number of a construction project's variables [16,17,18], regression analysis is simple in its use and provides adequate accuracy for conceptual project stages. For these reasons, it has been extensively applied for cost estimates in construction projects, e.g. in buildings [19] and bridges [20,21,22]. In addition to regression analysis, other techniques, such as neural networks and structural equation modeling have also been used for cost estimation purposes (e.g. [23,24]).

3. Proposed Model for Culverts Conceptual Cost Estimate

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. Specifically, following the statistical processing of data from recently constructed structures, regression models for the prediction of quantities of concrete and reinforcing steel are derived. The structure cost is then determined by multiplying the estimated quantities with the unit prices specified by the user. Furthermore, the available cost data allows for the total construction cost to be broken down in different construction activities. This cost breakdown can be used for the estimation of the other activities' cost, once the structure cost has been estimated by the regression models.

The aforementioned cost estimate model refrains from producing direct values of cost per surface area, as these values are typically heavily influenced by factors like the procurement method, the financial condition and capacity

of the construction companies, the financial circumstances (economic growth, inflation rate, financing conditions) and thus, they would substantially reduce the reliability of the model and its generalisation capability.

4. Database development

The developed database includes material quantities and design parameters from 104 culverts from two recently constructed motorways in Greece, the "Egnatia" Motorway and the "Ionia Odos" Motorway. The material quantities for all construction activities were recorded. These activities included 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 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 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. Specifically, the structures included in the database were designed in compliance with the German DIN codes and the Greek standard for earthquake loading. They 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 ranges 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 the remaining cost items (ground smoothing, finishings, drainage, joints). 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. Apparently, the structure represents the most important cost item accounting in average for 70.93% of the total cost. Earthworks and miscellaneous activities respectively represent in average the 18.23% and the 10.84% of the total cost. All cost categories present low variance.

Table 1. Culverts' sub-costs as percentages of total cost

	Earthworks	Structure	Miscellaneous
MIN	13.15%	69.56%	9.61%
MAX	20.38%	74.60%	12.86%
AVERAGE	18.23%	70.93%	10.84%
STD	3.20%	1.96%	1.31%

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 were particularly enlightening with regards to the culverts' design process which could be summarized as follows: 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. Based on the above, the designer determines the necessary clear width and height of the culvert. The dimensions and steel reinforcement of the culvert are finally calculated after taking into account the site's seismic conditions and the overburden height of the ground. Wingwalls are typically suspended from the side walls of the culvert and their design depends on site-related factors, such as the ground morphology, as well as on the height of the culvert.

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 already included in the aforementioned parameters, as they are used for the calculation of the culverts' net dimensions. The culverts database does not currently include adequate data samples for all the seismic zones of the Greek standard for earthquake resistant structures as the largest part of the sample has been designed with similar seismic parameters. Consequently, the earthquake conditions were excluded from the proposed material prediction models. The net height and width and the overburden height were selected as independent variables of the model, while the volume of concrete (V_c) and the weight of reinforcement steel (B_s) were 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 regression models determined are linear, of the form of eq.1 with Y standing for the dependent variables (V_c and B_s) and h_{net} , b_{net} and h_{over} being expressed in meters.

$$Y = a + b_o \times b_{net} + b_1 \times h_{net} + b_2 \times h_{over} \quad (1)$$

The equations 2 and 3 specifically provide predesign estimates for the volume of concrete and the weight of reinforcing steel for concrete cast-in-situ single box-shaped culverts. The quantities estimated include the box of the culvert, as well as the wingwalls.

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

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

The derivation of a regression equation is typically followed by statistical hypothesis tests to check the significance of the overall model and the independent variables, in tandem with a rationality check of the regression coefficients. In greater detail, the adjusted coefficient of determination (R^2) provides a measure of the total variability explained by the equation, while the F-value checks the hypothesis that the regression model does not capture the dependent variables' variability 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 equations and in particular, the R^2 , the results of the F-test (F-significance, F-value) and the p-values for the independent variables.

Table 2. Regression statistics

	V_e	B_s
R^2	0.908	0.844
F-value	290.654	159.436
F-significance	1.455E-44	8.499E-35
p-value b_{net}	4.578E-34	1.580E-25
p-value h_{over}	1.126E-19	1.020E-10
p-value h_{net}	0.007	0.011

6.2. Testing the linear regression assumptions

The R^2 values for the two regression equations exceed 84% and indicate that the proposed model captures the most substantial part of the total variability. The F-significance and the p-values verify that the regression equations 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.

Additionally, a multicollinearity check is necessary. 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 [25]. 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 [26] value of 10, while the pairwise correlations among explanatory variables are relatively low, indicating that multicollinearity was not an actual problem for the models.

Furthermore, 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 (homoscedasticity) [25]. 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 [27]. 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 was tested with White's general heteroscedasticity test [28]. The test's auxiliary regression was performed and the test statistic that equals the product of the sample size with the R^2 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.

Table 3: Pearson product-moment correlation coefficients and VIF for the data sample

	V _c	B _s	h _{over}	b _{net}	h _{net}	VIF
V _c	1.000					
B _s	0.928	1.000				
h _{over}	0.306	0.376	1.000			1.301
b _{net}	0.818	0.820	-0.123	1.000		1.565
h _{net}	0.667	0.681	0.336	0.512	1.000	1.738

6.3. Model validation

A good fit for a regression model does not always guarantee its validity. Cross-validation techniques are widely used to estimate generalization error, choose among various models, evaluate the prediction performance of a model and generally, determine if the model will function successfully in its intended operating environment [29]. A 10-fold validation method was implemented. In 10-fold cross-validation, the dataset is randomly divided in ten subsets (the folds) of approximately equal size. The regression model is then derived leaving out one of the subsets and the omitted subset is then used for testing. The aforementioned procedure is repeated for all the ten subsets and the selected error criterion is averaged. The Mean Absolute Percent Error (MAPE) was selected as the error measure. MAPE represents the average of deviations between predicted and actual estimates in absolute values expressed as percentage of the actual estimate. MAPE values for all ten testing samples for both regression equations are presented in Table 4 and reveal that the regression equations are able to predict the actual superstructure material quantities with an average error of less than 20 % (13.78% for the volume of concrete and 19.79% for the weight of reinforcing steel).

This error is considered acceptable according to the U.S. Department of Energy's directives for construction projects, which propose an accuracy range of ± 40 % for planning/feasibility estimates prepared prior to conceptual design [30]. AACE's typical accuracy ranges for class 4 estimates are -15% to -30% on the low side and +20% to +50% on the high side [15]. Besides, Ritz [31] proposes an acceptable accuracy range of ± 25 -30 % for construction cost estimates prepared prior to the project's conceptual design.

The derived MAPE values can be attributed to the lack of standardization in the selection of the culverts' cross section and reinforcement layout. Design standards do not dictate the use of specific shapes, cross sections and reinforcement schemes, but propose several design conditions and criteria that must be fulfilled. Furthermore, culvert construction usually constitutes part of a larger construction contract that involves several construction projects (bridges, culverts, underpasses, tunnels etc) with different parameters. The designer selects the dimensions and shapes for each structure considering the whole project, in order to maximize the construction process' standardization and achieve economy.

Table 4: MAPE values for testing samples

Testing Sample	MAPE values	
	V _c	B _s
1	12.19%	14.96%
2	9.31%	22.83%
3	7.15%	18,98%
4	24.94%	22.56%
5	11.16%	14.68%

6	10.63%	16.90%
7	7.15%	20.57%
8	18.48%	23.75%
9	18.95%	26.80%
10	17.86%	15.93%
Average	13.78%	19.79%

7. Conclusions

This paper presented a preliminary cost estimate model for culverts which consists of two linear regression equations derived from actual as-built data from 104 recently constructed culverts. The equations are able to predict the quantities of concrete and reinforcing steel of the culvert from its net width and height, as well as the overburden height. Following the estimation of material quantities, the structure cost estimation is achieved by multiplying the quantities by the proper unit prices as specified by the user. Following this, the culverts' total cost breakdown as observed in the actual construction data, can be used to derive the remaining cost elements (earthworks and miscellaneous). The proposed regression equations were statistically checked regarding their significance and the results confirmed the proposed equations' ability to capture more than the 84% of the variables' variability. Furthermore, relevant statistical checks confirmed that the data sample used for the development of the equations was free from the multicollinearity problem, while the assumptions of the correct application of the regression methodology were verified. Finally, the 10-fold cross-validation of the equations demonstrated that they are able to predict the actual culverts' material quantities with an average error of less than 20%, which is within the typical accuracy ranges for preliminary cost estimates. This research provides a reliable cost prediction model for culverts which is particularly valuable for the projects' stakeholders, as it only requires as input, data available at the early design stage.

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