Development of Cost Functions for Sewage Treatment Plants based on Conventional Activated Sludge Process

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Abstract

Objectives: The objective of the study is to develop CFs to estimate cost of STPs in the planning stage to facilitate selection of technology for Sewage Treatment Plant (STP). Methodology: The cost data for 30 existing STPs based on ASP technology, were collected, classified and updated to the base year of 2014 using the Construction Cost Indices (CCIs) published by Construction Industry Development Council of India. The regression analysis was performed with unit cost versus capacity in Microsoft EXCEL graphs and the equation with determination coefficient (R²) closer to one was selected as the Cost Function (CF). Findings: For validating the developed CFs, costs were predicted using the developed CFs for small, medium and large capacities and compared with the actual costs of STPs, Absolute Percentage Error (APE) for each STP and the MAPE as the mean of APE values for the three groups of STPs were derived. Similarly the MAPE values by comparing the predicted costs of STPs using common CF for all capacities with the actual costs were determined. The error measures MAPE values (as percentage) for separate CFs were 3.22, 7.72 and 2.35 for small, medium and large capacity groups respectively, which are within 10%, indicating highly accurate prediction of costs than with common function with MAPE values of 15.92, 15.88 and 16.8% respectively indicating good prediction only. Further Polynomial, logarithmic and power functions were found to be the best-fit equations for different capacity groups instead of power law as reported in the literature. Conclusions: Since the accuracy of prediction by separate CFs was found to be very high separate functions for each of the three capacity groups are necessary.

Keywords: Cost Function, Determination Coefficient, Mean Absolute Percentage Error, Regression Analysis, Sewage Treatment

1. Introduction

The urban population in India has increased from 12% in 1901 to 31.2% in 2011 and it is predicted that it would increase to 38.8% in 2026 and more than 50% in 2051 thus the demand for urban infrastructure facilities like water supply and sewage treatment and disposal is expected to rise sharply, posing a big challenge to urban planners and policy makers. This has thrown up two self-perpetuating problems of providing water supply and collection and disposal of sewage from these towns/cities.

The Government of India has taken up the planning and implementation of sewerage system with Sewage Treatment Plants (STPs) for all the cities/towns with the objectives of avoiding environmental pollution, reducing the health risks and thereby improving the health and hygiene conditions of the people.

There are number of STP technologies available to treat the sewage and produce effluent suitable for different options of disposal as well as reuse. To select the appropriate STP technology from alternative treatment technologies economic analysis is required for which construction
costs and Operation and Maintenance (O&M) costs of STPs are required.

In the framework of wastewater economics there are three methodologies to develop CFs for STPs:

- The STP is viewed as a system consists of number of components or subsystems, each of which is simulated in detail following an engineering approach to estimate cost.
- In the factor method, major cost drivers are related to specific major cost parameters and are directly estimated.
- Statistical methods are used to relate the cost to the main variable of the facility when actual cost data are available.

The third methodology is generally adopted in the development of CFs for STPs by regression analysis of the historical cost of the STPs. As stated by Qasim the CFs for STPs are mathematical models and quantified as a function of process size (e.g. capacity or flow rate) or population equivalent (PE) by the use of a non-linear function.

Cost data collected were statistically analysed and CFs were developed to predict unit cost of construction with PE as well as design flow as variables.

Friedier and Pisanty have developed CFs for STPs by statistically analyzing the costs of 55 STPs constructed in Israel. Nogueira et al. have developed CFs for investment and operation costs of STPs, using power law and found that the per capita cost decreases with increase of population served.

In India no such studies has been reported on the development of CF for STPs. This paper presents a study on the development of CF based on historic cost data for STPs based conventional Activated Sludge Process (ASP), which is one of the popularly adopted technologies for STP in India and to test the suitability of a single common CF for all capacities.

2. Methodology

In India 88% of the towns classified into class III–V are smaller and producing sewage flows of 0.5–5 Million Litres per Day (MLD), while class I and II cities are producing sewage flows from 5–120 MLD. The unit cost of STP in general decreases with increase in capacity of STP following economy of scale and hence adopting a single CF for all the capacities may not yield accurate cost estimate and number of CFs may be required for different capacity ranges. Therefore, capacities of STPs were grouped into three capacity ranges viz., small, medium and large capacities as shown in Table 1.

Table 1. Capacity ranges and suitability for types of towns

| Classification of capacities | Capacity range, MLD | Suitable for |
|-----------------------------|---------------------|-------------|
| Small, $Q_s$                | 0.5 – 5             | Population (thousands) |
| Medium, $Q_m$               | 5 – 50              | Class III – V |
| Large, $Q_L$                | 50 – 120            | Class II     |
|                             |                     | Class I      |

The methodology adopted for the development of CFs for STPs based on ASP technology using the historic cost data consists of the following steps:

- Collection of construction cost data of STPs.
- Categorization of cost data group-wise and deriving unit costs.
- Updating the unit costs to base year of 2014 using CCI.
- Preparation of input data – capacity versus unit cost for regression analysis.
- Performing regression analysis in Microsoft EXCEL spread sheet.
- Selection of the best-fit equation that has the determination coefficient $R^2$ value closest to one.

The construction cost data for 30 STPs based on ASP technology constructed in Tamil Nadu, were collected and the unit costs (per MLD) of STPs were derived. The data were categorized into three capacity groups and the details are furnished in Table 2.

These cost data were related to STPs constructed in the years from 2007 to 2012 and for updating the costs to the base year of 2014 the CCIs published by Construction Industry Development Council (CIDC) of India for urban infrastructure with a base value of 100 in the year 2007 for Chennai city were used. The CCIs for urban infrastructure published by CIDC applicable for Chennai for the years from 2007 to 2014 are furnished in Table 3.

With the updated cost data for 2014 two dimensional input files of capacity with corresponding unit costs of STPs were prepared for regression analysis. The regression analysis was performed in Microsoft EXCEL graphs with trend lines using five regression equations, viz., polynomial function, power law, logarithmic function,
exponential function and linear equation for the development of CFs for each group of capacities and one as common for all the capacities. The graphs provided the regression equations and values of determination coefficient $R^2$. The equation among the five equations that has $R^2$ value closest to one was selected as the best-fit CF.

The developed CFs for the three capacity groups and the CF common to all capacities were validated by predicting costs using each of the CFs for the capacities of STPs for which costs are available and comparing with construction costs and the error measures in terms of Absolute Percentage Error (APE) and Mean Absolute Percentage Error (MAPE) were determined using the Equation (1) and (2) suggested by Ashuri and Lui.

\[
APE = \frac{|Y_p(i) - Y_A(i)| \times 100}{Y_p(i)} \quad (1)
\]

\[
MAPE = \frac{1}{N} \sum_{i=1}^{N} \frac{|Y_p(i) - Y_A(i)| \times 100}{Y_p(i)} \quad (2)
\]

Where
- $Y_p$ is the predicted cost,
- $Y_A$ is the updated actual cost, and
- $N$ is the number of data considered in the analysis.

The following interpretation of MAPE values suggested by Lewis was used to find the accuracy of prediction by the CFs.

- Less than 10% is highly accurate prediction,
- 10% to 20% is good prediction,
- 20% to 50% is reasonable prediction, and
- 50% or more is inaccurate prediction.

### 3. Results and Discussion

The developed CF graphs with the capacities of STPs in X-axis and unit costs of STPs (US$ 10^6) in Y-axis with trend lines for small, medium and large capacity STPs based on ASP technology and one common to all capacities using the updated actual costs to the base year 2014 are furnished in Figures 1 to 4.

The developed CFs for small, medium and large capacity groups of STPs and one common to all capacities are furnished in Equation (3) to (6).

\[
C_p = -0.008Q_s^2 + 0.014Q_s + 0.293 \quad (R^2 = 0.934) \quad (3)
\]
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\[ C_M = 0.205e^{-0.01Q_M} \quad (R^2 = 0.975) \]  

\[ C_L = 0.864Q_L^{-0.36} \quad (R^2 = 0.963) \]  

\[ C_C = 0.021n(Q_C) + 0.245 \quad (R^2 = 0.369) \]

Where

\( C_S, C_M \) and \( C_L \) are unit costs of STPs for small, medium and large capacity STPs respectively; US$ 10^6/MLD,

\( C_C \) is the unit cost for all capacities of STPs; US$ 10^6/MLD,

\( Q_S, Q_M, Q_L \) and \( Q_C \) are the capacities of small, medium, large and common for all capacity, MLD.

In this study it was found that the CF equations for small, medium and large capacities are based on polynomial, exponential and power law respectively and the common CF for all capacities was based on logarithmic function as against the power law, as the general form of non-linear function for most of the CFs reported by Sato et al.\(^4\). The values of determination coefficient \( R^2 \) of the CFs for small, medium and large capacities were 0.934, 0.975 and 0.963 respectively and are closer to one and therefore, these CFs represent the data very well, while \( R^2 \) value for the common CF is only 0.369 and hence the equation is not well representing the data.

Further for validating the CFs, costs were predicted using the developed Equation (3) to (5) for small, medium and large capacities and compared with the updated construction costs of STPs for the base year of 2014, APE for each STP and the MAPE as the mean of APE values for the three groups of STPs were derived. Similarly the APE values and MAPE value by comparing the predicted costs of STPs using common CF as per Equation (6) with the updated construction costs were determined. The comparisons for the three groups of capacities with separate CFs and common CF with APE and MAPE values are furnished in Tables 4 to 6 respectively.

From Tables 4 to 6 it could be seen that the error measures MAPE values (as percentage) for CFs for each group (3-5) are 3.22, 7.723 and 2.354 for small, medium
Table 4. Comparison of predicted costs for small capacity STPs from the developed CFs with updated construction costs (all the costs are in Million US$)

| capacity of STP, MLD | Updated unit construction cost of STP (US$ 10^6) | Predicted cost of STP (Col.3) | Error (Col.3-Col.2) | APE (%) | Predicted cost of STP with common CF (Col.6) | Error (Col.6-Col.2) | APE (%) |
|----------------------|---------------------------------|-----------------------------|-------------------|--------|---------------------------------|-------------------|--------|
| (1)                  | (2)                             | (3)                         | (4)               | (5)    | (6)                             | (7)               | (8)    |
| 2.20                 | 0.282                           | 0.285                       | 0.004             | 1.234  | 0.229                           | -0.052            | 22.829 |
| 2.24                 | 0.286                           | 0.284                       | -0.002            | 0.530  | 0.229                           | -0.057            | 24.842 |
| 2.96                 | 0.268                           | 0.264                       | -0.003            | 1.242  | 0.223                           | -0.044            | 19.855 |
| 3.50                 | 0.236                           | 0.244                       | 0.008             | 3.334  | 0.220                           | -0.016            | 7.238  |
| 3.90                 | 0.227                           | 0.226                       | -0.001            | 0.567  | 0.218                           | -0.009            | 4.326  |
| 3.99                 | 0.239                           | 0.221                       | -0.018            | 8.074  | 0.217                           | -0.022            | 10.150 |
| 4.20                 | 0.185                           | 0.211                       | 0.026             | 12.370 | 0.216                           | 0.032             | 14.647 |
| 4.84                 | 0.173                           | 0.173                       | 0.000             | 0.030  | 0.213                           | 0.040             | 18.764 |
| 4.86                 | 0.169                           | 0.172                       | 0.003             | 1.597  | 0.213                           | 0.044             | 20.641 |

MAPE= 3.220%

Table 5. Comparison of predicted costs for medium capacity STPs from the developed CFs with updated construction costs (all the costs are in Million US$)

| Capacity of STP, MLD | Updated unit construction cost of STP (US$ 10^6) | Predicted cost of STP (Col.3) | Error (Col.3-Col.2) | APE | Predicted cost of STP with common CF (Col.6) | Error (Col.6-Col.2) | APE |
|----------------------|---------------------------------|-----------------------------|-------------------|-----|---------------------------------|-------------------|-----|
| (1)                  | (2)                             | (3)                         | (4)               | (5) | (6)                             | (7)               | (8) |
| 6.92                 | 0.185                           | 0.191                       | 0.007             | 3.506| 0.206                           | 0.022             | 10.530 |
| 7.00                 | 0.187                           | 0.191                       | 0.004             | 2.073| 0.206                           | 0.019             | 9.173 |
| 7.38                 | 0.190                           | 0.190                       | 0.001             | 0.344| 0.205                           | 0.015             | 7.445 |
| 7.65                 | 0.179                           | 0.190                       | 0.010             | 5.499| 0.204                           | 0.025             | 12.161 |
| 8.70                 | 0.180                           | 0.188                       | 0.008             | 4.421| 0.202                           | 0.022             | 10.966 |
| 9.63                 | 0.177                           | 0.186                       | 0.011             | 5.167| 0.201                           | 0.024             | 12.170 |
| 9.00                 | 0.177                           | 0.187                       | 0.009             | 4.643| 0.201                           | 0.022             | 11.141 |
| 10.62                | 0.173                           | 0.184                       | 0.011             | 5.896| 0.198                           | 0.024             | 12.273 |
| 12.05                | 0.161                           | 0.182                       | 0.020             | 11.152| 0.195                           | 0.034             | 17.292 |
| 12.25                | 0.163                           | 0.181                       | 0.018             | 9.976| 0.195                           | 0.032             | 16.223 |
| 13.07                | 0.172                           | 0.180                       | 0.008             | 4.293| 0.194                           | 0.021             | 11.070 |
| 23.65                | 0.142                           | 0.162                       | 0.019             | 12.018| 0.182                           | 0.039             | 21.656 |
| 23.85                | 0.148                           | 0.162                       | 0.014             | 8.417| 0.182                           | 0.034             | 18.537 |
| 40.00                | 0.106                           | 0.137                       | 0.031             | 22.881| 0.171                           | 0.065             | 38.107 |
| 40.00                | 0.113                           | 0.137                       | 0.024             | 17.532| 0.171                           | 0.058             | 33.815 |

MAPE= 7.723%

MAPE= 7.723%

MAPE= 15.921%

and large groups respectively, which are within 10%, indicating highly accurate prediction of costs according to Lewis. The MAPE values (as percentage) when predicted with common function for all capacities are 15.921, 15.884 and 16.799 respectively for small, medium and large groups,
which are between 10 and 20% indicating good prediction of STP costs. However the accuracy of prediction with separate CFs for small, medium and large capacities is very high than that of single common CF, hence, single common CF for all capacities is not preferable and number of CFs for different groups of STPs is required.

4. Conclusion

From the study it was found that the best-fit equations depend on the nature of the data. Polynomial, logarithmic and power functions were found to be the best-fit equations for the CFs for small, medium and large groups of capacities of STPs instead of power law as suggested in the literature. Further the accuracy of prediction with CFs for small, medium and large capacities was found to be very high than that of single common CF and hence separate CFs for each of the three capacity groups are necessary instead of single CF for all capacity STPs to predict accurate costs of STPs.

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