Robust design for minimisation of life cycle costs of road embankments on soft soil

Conception robuste pour la minimisation des coûts intégraux de remblais de route sur sols mous

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ABSTRACT: ROADRUNNER is a decision support system for preliminary design of motorway embankments on soft soil. The system may be used to calculate life cycle costs. This paper compares a new approach for optimisation of design to two traditional approaches. The new approach involves the selection of the set of design parameters which is least sensitive, or most robust, to uncertain factors in the design. The approaches are applied to a case study.

RÉSUMÉ: ROADRUNNER est un système interactif d'aide à la décision pour la conception préliminaire des remblais sur sols mous. Le système peut être employé pour calculer des coûts intégraux. Cet article compare une nouvelle procédure pour l'optimisation de la conception à deux procédures traditionnelles. La nouvelle procédure comporte la sélection de l'ensemble de paramètres de conception qui est moins sensible aux facteurs incertains dans la conception. Les procédures sont appliquées à une étude de cas.

1 INTRODUCTION

Dealing with adverse conditions has become a second nature for the Dutch. Most of the Netherlands economical activities are concentrated in the western part of the country in the delta of the Meuse and Rhine rivers. The soft and compressible soils in this area pose serious problems in the construction of infrastructure. Construction may take years due to slow consolidation; also, maintenance costs are high because of large residual settlements. The traditional design approach is driven by initial costs which prohibits the use of piled embankments and light weight fill materials. With maintenance budgets at the Ministry of Transport, Public Works and Water Management being reduced, the design approach is shifting towards life cycle costing, i.e. minimisation of total cost of construction and maintenance.

In the preliminary design stage, engineers face the problem of selecting a construction method that satisfies both budget and technical constraints, with only limited soil data available. To aggravate the problem, different consultants may come up with significantly different predictions. In order to resolve these problems the Road and Hydraulic Engineering Division has developed the decision support system ROADRUNNER, named after the supersonic cartoon character. Features of ROADRUNNER are described in Barneveld & Venmans (1999).

ROADRUNNER predicts the performance of different construction methods with respect to life cycle costs. Soil data in ROADRUNNER is derived from large databases, requiring only a single CPT to be input at runtime. The design methods for the different construction methods in ROADRUNNER are firmly rooted in Dutch practice and are well documented. Continuity towards the final design stage is provided by requiring consultants to make their designs comply with the implementation of design methods in ROADRUNNER.

A case study is presented to compare the current approach to the design of motorways embankments on soft soil to a new and efficient approach for minimisation of life cycle costs.

2 DESCRIPTION OF THE CASE STUDY

An embankment with a crown width of 49 m is to be built for the support of the new 2 × 4 lane motorway A2 between Amsterdam and Utrecht. Near Breukelen the motorway will pass over a railroad by a bridge, which requires the embankment to be raised to 5 m above ground level. The subsoil consists of 2 m soft organic silty clay and 2 m mesotrophic fibrous peat, underlain by a thick sand layer of Pleistocene age. Given these conditions, the main design concern is the longitudinal roughness of the road surface during its service life.

Two construction methods are to be evaluated. The first method ('pfd') employs prefabricated band drains and a sand fill with thickness equal to the net embankment height plus the amount of settlement occurring before the pavement is applied. The second method ('pfd+ts') employs prefabricated band drains and the sand fill plus a temporary surcharge. Compression of the soft layers induced by the surcharge is assumed to reduce residual settlements. The time allowed for construction (raising the fill and consolidation of the subsoil) is 3 years.

ROADRUNNER is used in the following three design approaches to select the best construction method:

1. In the traditional approach, residual settlements are minimised using average values of soil parameters; this is the current practice.
2. In the traditional life cycle cost approach, total costs of construction and maintenance during the service life of the road are minimised, using average values of soil parameters.
3. In the robust life cycle cost approach, total costs of construction and maintenance are minimised considering the effects of uncertainties in both soil properties and design methods.

3 TRADITIONAL APPROACH

3.1 *Procedure*

Bridges have their foundations into the Pleistocene sand layer and show no residual settlements. Differential settlements will occur at the transition to the embankment built on Holocene soft soil subject to creep. Transition slabs reduce the effects of differential settlements on longitudinal roughness of the road surface (Fig. 1). Dutch guidelines for motorway maintenance state that the change of slope of the road surface from bridge deck to transition slab should not exceed +1:100 for reasons of traffic safety (Fig. 2). Initially, the road surface may be given a counterslope of -1:150. If L_{slab} denotes the length of the transition slab, differential settlements in excess of $L_{slab}/60$ will require reprofiling the road surface near the transition. So, for a typical slab length of 6 m the maximum differential settlement equals 0.10 m.

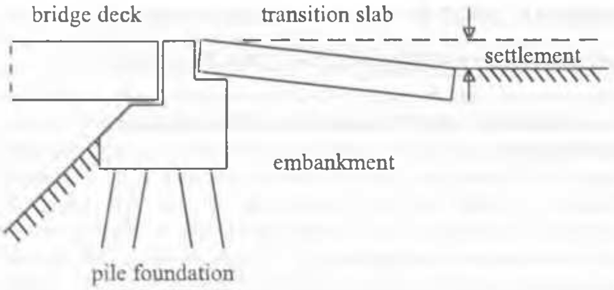

Figure 1. Longitudinal section at the transition from bridge to embankment.

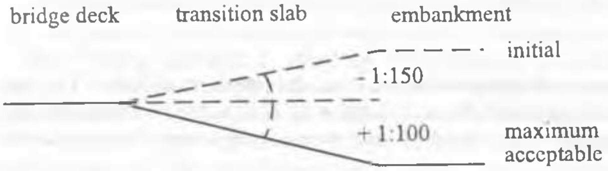

Figure 2. Initial and maximum acceptable road profile.

Six ROADRUNNER runs are required to minimise the residual differential settlements occurring during the 24 year service life of the road. After this period, pavement and transition slabs are assumed to be completely rebuilt.

3.2 *Results*

The residual settlement for the pfd method is 0.19 m. The residual settlement for the pfd+ts method as a function of the height of the temporary surcharge is given in Figure 3.

In this traditional design approach, the pfd+ts method with a temporary surcharge of 4 to 5 m should be preferred. The predicted residual settlements of 0.12 m are such that the longitudinal roughness will become unacceptable after 15 years and reprofiling of the road surface will be required. After that, the roughness will be satisfactory for the rest of the service life.

4 TRADITIONAL LIFE CYCLE COST APPROACH

4.1 *Procedure*

Optimisation for life cycle costs requires a cost model to be added. For the sake of clarity, the model used in this case study is a simplified submodel of the model in ROADRUNNER.

Construction costs for ground improvement, earthworks and transition slabs are readily calculated from volumes per cross section. The length of the embankment is taken as 45 m, the length over which the temporary surcharge needs to be applied for full effect at the transition slabs and a gentle transition to the rest of the embankment. All costs for ground improvement and earthworks are assumed to be made in the first year. Costs for the transition slabs are made in the end of year 3. Expenses C_i in any year i are converted to their net present values C_1 in year 1 according to Equation 1.

$$C_1 = \frac{C_i}{(1+d)^i} \qquad (1)$$

where d is the discount rate.

The main part of the maintenance costs is due to the measures for traffic diversion which have to be taken to guarantee the safety of workers. In this case study the maintenance costs for each time the road surface is reprofiled are assumed to be EUR 130,000 (1 EUR = 0.90 US$). Costs associated with loss of productivity due to traffic congestion are not included. Neither are the maintenance costs reduced in case the reprofiling coincides with the periodic replacement of the wearing course, typically every 10 years.

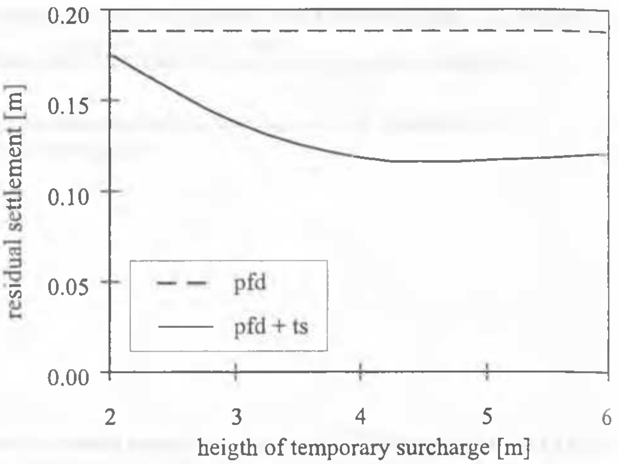

Figure 3. Residual settlements for both construction methods as a function of height of the temporary surcharge in the pfd+ts method.

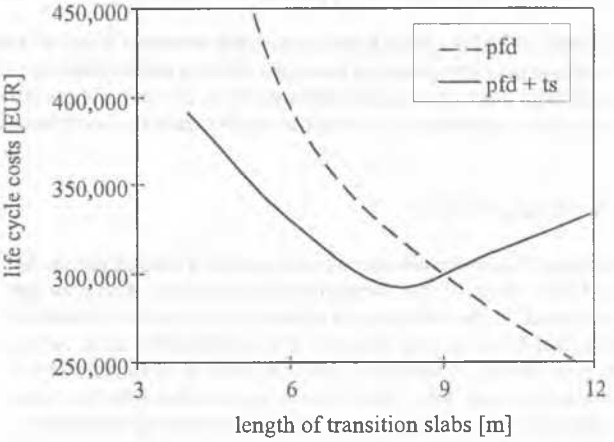

Figure 4. Life cycle costs for both construction methods as a function of the length of the transition slabs.

The number of times the road surface needs to be reprofiled is calculated by comparing the time-settlement curve of the embankment to the cumulative maximum differential settlements which can be absorbed by the transition slabs. The maintenance costs in any year of the 24 year service life of the road are converted to their net present values and added to the construction costs. The life cycle costs given pertain to a single embankment.

As a first step in the traditional life cycle cost approach, the effect of varying surcharge height may be studied, as in the traditional approach. The second step involves minimising life cycle costs for different lengths of the transition slabs. The complete analysis requires 48 ROADRUNNER runs.

4.2 *Results*

The life cycle costs for the pfd method are EUR 393,700, half of which are due to reprofiling the road surface every 7 years. The plot of life cycle costs as a function of the height of the temporary surcharge in the pfd+ts method is very similar to figure 3, only with a minimum of EUR 318,900 at 3m surcharge height.

Figure 4 depicts life cycle costs as a function of the length of the transition slabs. It now appears that increasing the length of the slabs, and thus maximum allowable settlement, is a very cost effective measure for the pfd method. The reduction in maintenance costs easily outweighs the larger costs of longer transition slabs. The advantage of the pfd method over the pfd+ts method is due to the lower construction costs of the embankment.

According to the traditional life cycle cost design approach, the pfd method should be preferred, using transition slabs with a length of 12 m, which is the practical maximum.

Table 1. Noise parameters in the design of the pfd and pfd+ts methods.

Parameter	coefficient of variation	source of uncertainty
Friction ratio	0.25	S, T
Volume weight of fill material	0.05	S
Volume weight of soft soil	0.05	C
Buisman-Koppejan compression constant	0.30	C
Total thickness of soft soil	0.10	S
Coefficient of consolidation for vertical flow	0.20	C, T
Ratio of horizontal to vertical permeability	0.30	C, T
Depth of ground water table	0.25	S
Ratio of primary settlement to settlement after 10,000 days	0.20	C
Required average degree of consolidation during fill placement	0.05	C
Effectivity of temporary surcharge	0.05	D
Fraction of time for fill placement to be added to consolidation time	0.25	D

Table 2. Orthogonal array (type L9) used to define parameter values x_{ki} in the test runs with ROADRUNNER.

	Parameter x_{ki}			
Test run i	k=1	k=2	k=3	k=4
1	-1	-1	-1	-1
2	-1	0	0	0
3	-1	1	1	1
4	0	-1	0	1
5	0	0	1	-1
6	0	1	-1	0
7	1	-1	1	0
8	1	0	-1	1
9	1	1	0	-1

5 ROBUST LIFE CYCLE COST APPROACH

5.1 *Procedure*

Many input parameters which affect the performance of the pfd and pfd+ts methods are stochastic, i.e. their actual value is uncertain. Also, the mathematical design rules for both methods may contain uncertainties. Generally both types of uncertainty are impossible or expensive to control. Instead, the robust life cycle cost approach aims to select the best combination of design parameters which can be controlled. The best combination is the combination which is least sensitive i.e. most robust to the variations in the 'noise' parameters of which the value is uncertain.

Table 1 lists the noise parameters involved in the design with ROADRUNNER, their uncertainty due to either spatial variability (S), imperfect sampling and testing (T), the use of correlations in ROADRUNNER (C), or imperfect design rules (D).

The coefficients of variation of most parameters are derived from databases. In ROADRUNNER all soil parameters are determined from their correlation with the friction ratio. The coefficients of variation given in Table 1 pertain to the standard error of the correlation, i.e. after removal of the regression trend. The main source of error in the friction ratio is the accuracy of the measurement of cone resistance and sleeve friction in very soft soils. The variation in the rate of consolidation by vertical drains is due to uncertainties in the assessment of well resistance of the drains, permeability and radius of the smear zone. Also, horizontal permeability is rarely measured in Dutch practice. The given value of the coefficient of variation of the total thickness of the soft soil is valid only if the CPT used as input in ROADRUNNER is performed less than 50 m from the location of the embankment for which the design is made. For larger distances, the coefficient of variation will be in the order of 0.25.

If each parameter in Table 1 takes 3 possible values (low - average - high) the evaluation of their combined effects on the life cycle costs by a full factorial analysis would require millions of ROADRUNNER test runs. A more elegant and efficient approach was first developed by Tagushi for quality improvement of industrial processes. This approach uses orthogonal arrays to define the settings of the parameters in the test runs. Orthogonal arrays stipulate the way of conducting the minimal number of test runs which could give the full information of all parameters that affect life cycle costs. An example of an orthogonal array is given in Table 2.

The orthogonal array in Table 2 enables the determination of the effects of 4 parameters with each 3 values in only 9 test runs, opposed to a full factorial approach which would require $3^4 = 81$ test runs. In the method presented here, x_k are actual parameters and not level settings as in the conventional Tagushi approach. Values of x_{ki} of -1, 0 and 1 are the normalised values of the noise parameters z_{ki} in Table 1, respectively corresponding to $\mu_{zk} - \sigma_{zk}$, μ_{zk} and $\mu_{zk} + \sigma_{zk}$. Thus, x_k has mean 0 and standard deviation 1.

The robust design for minimisation of life cycle costs consists of the following steps for each construction method:

1. Select the noise parameters for which the effects are to be evaluated. In this study all parameters in Table 1 are included. In subsequent analyses, noise parameters which are known to have little effect may be excluded.
2. Select the controllable design parameters. For the pfd and pfd+ts method the design parameters are the centre-to-centre distance of the drains and the length of the transition slabs; for the pfd+ts method also the height of the temporary surcharge is considered.
3. Calculate life cycle costs in ROADRUNNER test runs with noise parameters defined by a L27 orthogonal array and design parameters defined by a L9 array. This requires a total number of 729 test runs.
4. For each of the 9 settings of the design parameters, determine the variation of life cycle costs. As a measure this study uses the original signal-to-noise criterion S/N_i by Tagushi (Eq. 2), adding up the life cycle costs LCC_{ki} for the 27 settings of the noise parameters.

$$S/N_i = -{}^{10}\log\left(\frac{\sum_{k=1}^{K} LCC_{ki}}{K}\right) \tag{2}$$

5. Segregate the individual effects of the design parameters. This is possible under the assumption that the main effects of the design parameters are independent. Under this assumption, the effect of each parameter can be linear, quadratic or of higher order, but the method assumes that there exists no cross-product effects (interactions) among the individual design parameters.
6. Inspect the output to determine if interactions between design parameters exist.
7. Select optimum values of the design parameters, giving minimal life cycle costs according tot the *S/N* criterion.
8. Select the construction method with minimal life cycle costs according to the *S/N* criterion.

The analysis may be continued to derive partial safety factors for the noise parameters with the largest impact on the life cycle cost. The partial safety factors may be used in further analytical or numerical design calculations in the final design stage. The partial safety factors are determined in such a way that the probability of the costs exceeding a certain threshold is acceptable. The following procedure is used.

1. Calculate life cycle costs using ROADRUNNER for the best construction method with the optimum set of design parameters, and the noise parameters defined by a L27 orthogonal array. This requires 81 test runs.
2. Perform a regression analysis, fitting a first order polynomial in x_k to predict life cycle costs LCC_i (Eq. 3).

$$L\hat{C}C_i = a_0 + \sum_{k=1}^{K} a_k x_{ki} + \varepsilon_i \qquad (3)$$

Here, a_0 and a_k are the regression coefficients and ε_i is the regression error. The expected value of the life cycle costs is equal to a_0. The standard deviation is given by the root of the sum of the squares of the coefficients a_1 through a_k. Interactions between the parameters x_k are ignored in this study. If desired, higher order orthogonal arrays might be used to define test runs on which regression analysis produces unbiased estimators of the main effects, even if interactions exist.

3. Decide which noise parameters have the largest percentage contribution to the variation of life cycle costs.
4. For these parameters, determine the design point in a level II mean value probabilistic analysis. 'Failure' is defined as the life cycle costs exceeding a certain threshold, for instance taken as the 90% upper boundary.
5. Calculate the partial safety factors.

5.2 *Results*

Results for all approaches are summarised in Tables 3a and 3b. According to the robust life cycle cost approach the pfd-method should be preferred. Expected life cycle costs of the pfd+ts method (EUR 333,400) are considerably higher than of the pfd method. Also, the coefficient of variation is much higher (27 %).

The sensitivity analysis of the optimum design of the pfd method shows that 90 % of the variation in life cycle costs is caused by three noise parameters: friction ratio, compression constants and ratio of primary to total settlements after 10,000 days. These parameters have a large effect on secondary settlements.

The main sources of variance in the life cycle costs of the pfd+ts method are layer thickness, coefficient of consolidation, required degree of consolidation during fill placement and effectivity of the temporary surcharge. These parameters have an effect on secondary settlements and consolidation rate. Thus, it appears that time is a much more crucial factor in the pfd+ts method than in the pfd method. In the pfd+ts method, time is lost by placing the additional 4 m of surcharge, which reduces the time available for consolidation. Also, the permeability of the soft soil is lower because of the additional compression under the surcharge.

The determination of partial safety factors is straightforward and is not shown here for reasons of brevity.

6 CONCLUSIONS

6.1 *Comparison of approaches*

By inspection of Table 3b, these thoughts fall into our minds.

The traditional approach leads to excessive life cycle costs, caused by the sensitivity of the pfd+ts method to noise parameters and by the sensitivity of the 6 m transition slabs to residual settlements of the embankment.

The robust life cycle cost approach leads to the same optimum construction method as the traditional life cycle cost approach, with the same settings for the design parameters. However, the expected life cycle costs are higher than predicted by the traditional life cycle cost approach (EUR 245,000). This is due to maintenance costs caused by an unfavourable combination of the noise parameters, which is not taken into account in the traditional life cycle cost approach. In this case the life cycle cost function is non-linear.

A better estimate of the actual maintenance costs can be obtained by monitoring of settlements and pore pressures during construction and inverse analysis of compression and consolidation parameters.

Table 3a. Values of design parameters for optimal designs according to different approaches.

approach	centre-to-centre distance of drains	length of transition slabs	height of surcharge
	m	m	m
traditional	1.0	6	4
traditional life cycle costs	1.0	12	0
robust life cycle costs	1.0	12	0

Table 3b. Life cycle costs of optimal designs according to different approaches.

approach	mean life cycle costs	standard deviation of life cycle costs	coefficient of variation
	EUR	EUR	%
traditional	456,700	282,800	62
traditional life cycle costs	274,800	52,700	19
robust life cycle costs	274,800	52,700	19

The robust life cycle cost approach offers a number of advantages over the traditional approaches:

- The optimum design is not only based on minimal expected costs, but also on the variance of the costs.
- The sensitivity analysis identifies the noise parameters with the largest impact on life cycle costs. The site investigation for the final design and the monitoring programme during construction should focus on these parameters. In this way the most cost-effective improvement of the design is attained.

The robust life cycle cost approach is computationally the most intensive. However, a typical optimisation takes less than 15 minutes owing to the use of plug-in tools and spreadsheets dedicated to data reduction.

6.2 *Further developments*

Further development of the robust life cycle cost approach should be directed along the following paths.

The procedure may be improved to deal with interactions among design parameters.

The approach may be extended to include contingency plans. A contingency plan is to be implemented in case the monitoring of construction reveals that unfavourable conditions exist. One such plan might involve the replacement of part of the fill by light weight material. In the light of the unfavourable conditions, the application of light weight fill materials may have lower life cycle costs than the original design. The robust life cycle cost approach could be used to optimise the thickness of the light weight material.

The application of the approach to many different cases may disclose that the same small number of noise parameters always determines life cycle costs. This allows a simplification of the procedure and identifies areas in which improvements of sampling and testing methods and design models are most effective.

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