Life cycle cost optimisation of bridge approach constructions in local and national roads in the Netherlands

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Abstract

The current practice of road construction on soft ground frequently leads to a 'bump at the end of the bridge', at the interface between bridge and road embankment. Maintenance is costly and causes disruption of traffic. The main problems for bridge approach zones were identified in a literature survey and by interviewing expert consultants. Selection of an appropriate method to reduce post-construction settlements appears to be a critical factor.

For a number of proven methods for settlement mitigation post-construction settlements, frequency of maintenance and life cycle costs were determined for a variety of ground conditions, using the design support system MRoad. Especially for low-lying roads light weight material such as EPS appears to be the most attractive solution, based on life cycle costs. Recommendations for design of a proper bridge approach construction will be made available in a CROW publication in 2011 [1] and by the web tool Road Analysis Module – Bridge Approach Constructions (RAM-BAC, [2]).

The current paper illustrates the background of the life cycle cost calculations. Design charts compare life cycle cost of different construction methods.

INTRODUCTION

The interface between road embankment and bridge is one of the few locations in a road where structural, pavement and geotechnical engineers must work together to warrant a long trouble free performance. Practice shows the results of this cooperation are frequently unsatisfactory, and clearly visible to the public by the telltale sign of 'the bump at the end of the bridge'. This bad publicity for the engineering community makes one wonder why it is so difficult to design and construct a well performing bridge approach construction.

Multiple studies suggest that maintenance costs are substantial. Briaud e.a. [3] estimate the yearly damage to 25 % of 600,000 bridges in the United States to be in the order of $ 100 million (1997), or $ 150 average per bridge every year. Deltares [4] estimates the yearly maintenance cost of a total of 3,500 highway bridges and structures in the Netherlands as € 5 million to € 10 million (2010), or € 1,500 to € 3,000 average per bridge every year. These numbers are huge, and the significant difference between the US and Dutch average cost may reflect many factors involving design, construction, materials, traffic characteristics, soil conditions and professional and asset management practices. The authors are curious to learn about similar studies worldwide.

SELECTION OF A METHOD FOR REDUCING POST-CONSTRUCTION SETTLEMENTS

The recent report by the working group ‘Effective bridge approach constructions’ of Dutch research centre CROW [1] presents an overview of the main technical factors affecting performance of these constructions. The overview is based on a literature survey, a session with expert consultants and contractors, and interviews with administrators of local, regional and national roads. The list of factors with possibly detrimental effects on performance is astoundingly long, including soil settlement in embankments, approach fill material, abutment foundation type, abutment type, structure type, joints, approach slab, paving and construction methods.

Both Briaud [3] and CROW [1] studies agree that the main cause of ill performing bridge approach constructions is post-construction settlement of compressible natural soil under the weight of the embankment. The design question is to select a construction method for the embankment that reduces or eliminates post-construction settlements. Construction methods range from installation of vertical band drains and temporary surcharging to using an EPS fill that exerts no additional stress on the subsoil. The first method is relatively cheap but takes a year or longer to complete. An EPS fill is more expensive but can be raised in a couple of weeks. Usually, costs for maintenance are hardly taken into account when selecting a construction method.

In the early stages of a project consultants face the problem of selecting a construction method that satisfies budget, time and technical constraints, with only limited soil data available. Any initial mismatch between these constraints will propagate through further design and construction and inevitably lead to poor performance during operation.

The CROW report [1] presents of decision support matrix to guide the selection of proper construction methods for embankment and bridge abutment, both for new constructions and reconstruction. The decision support matrix requires input for allowable post-construction settlement, allowable longitudinal slope of the pavement, length of the approach slab, time available for construction, service life, road type, abutment type. The results include construction method, life cycle costs and maintenance frequency.

A simplified version of the decision support matrix can be accessed by the web tool ‘Road Analysis Module – Bridge Approach Constructions’, RAM-BAC, or ‘Weg Analyse Module – Overgangs-constructies’ in Dutch [2]. With a few clicks the user enters the type of road, available time for construction and the soil conditions, by making a selection from eleven soil profiles that represent the Dutch subsoil variation. RAM-BAC than presents a top five of suitable construction options for the embankment, ranked by life cycle cost. The life cycle costs are given as ratios relative to the construction cost of a sand fill. RAM-BAC can be accessed with the browser of a smartphone (figure 1), allowing on-the-spot decision making in an early project stage.

The following chapter describes the backgrounds of this web tool.

Top 5 construction methods

Name	LCC ratio*	maintenance frequency	construction cost ratio*
Sand+drains+temp surcharge	2.7	0	2.7
Sand+drains+temp. surcharge+gtx	3.1	0	3.1
EPS fill	3.3	0	3.3
Sand+Beaudrain	3.4	0	3.4
Sand+Beaudrain+temp. surcharge	3.4	0	3.4

* ratio with respect to construction cost of sand fill

Figure 1 : RAM-BAC on a smartphone (left); RAM-BAC output (right).

BACKGROUNDS OF ‘ROAD ANALYSIS MODULE – BRIDGE APPROACH CONSTRUCTIONS’

The main challenge in the development of RAM-BAC was to perform a large number of calculations of post-construction settlements for a variety of situations, and converting the post-construction settlements to life cycle costs. A high degree of automation is required to perform the 4x11x4x14 = 2464 calculations within reasonable time. This immense task was performed in two weeks using the software MRoad and post-processing in Excel spreadsheets. MRoad combines pavement design and geotechnical design for a highway, calculating pavement thickness, settlements during operation, space required for stable slopes and damage to the existing road caused by the widening of the road embankment [5]. Initial and life cycle cost can be analysed for comparison of alternative designs.

The core of MRoad is the two-dimensional settlement calculation according to the a-b-c isotache model. MRoad shares this core and its possibilities for simulating ground improvement methods with D-Settlement, an application widely used in the Netherlands for settlement analysis [6]. MRoad derives the initial construction cost of a given design from volumes and lengths of building materials. MRoad predicts maintenance by comparing settlements, slopes and curvatures to requirements related to safety and comfort.

This study considers four road types: a local road 0.4 m above ground level, a local road 7.0 m above ground level, a highway at 3.0 m above ground level, and a highway 7.0 m above ground level (figure 2). The variation in Dutch soil conditions is captured in eleven soil profiles, given in figure 3. Soil parameters for these profiles have been derived from databases compiled from a large number soil tests for large projects in the Netherlands.

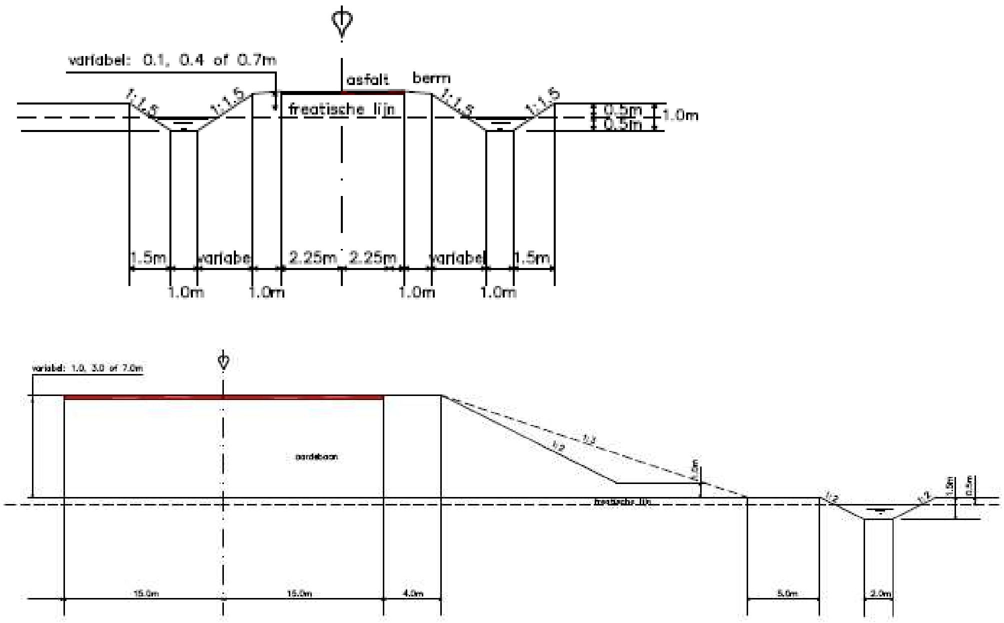

Figure 2 : Cross sections of a local road at GL+0.4 m (top) and a highway at GL+7.0 m (bottom).

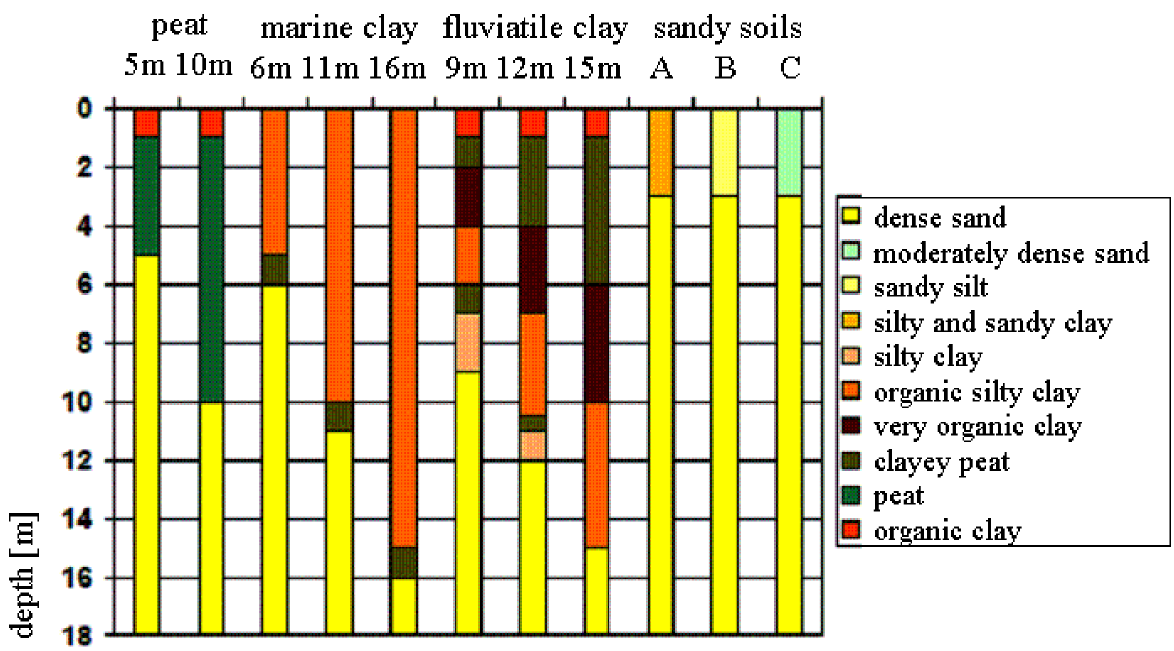

Figure 3 : Soil profiles used in this study.

Road cross sections and soil profiles have been combined and loading and drainage conditions were imposed specific to the following construction methods:

- sand fill;
- sand fill with 2 m temporary surcharge;
- sand fill with vertical band drains centre-to-centre 1 m;
- sand fill with vertical band drains centre-to-centre 1 m and 2 m temporary surcharge;
- sand fill with vertical band drains centre-to-centre 1 m and vacuum surcharging (Beaudrain method);
- sand fill with vertical band drains centre-to-centre 1 m and vacuum surcharging (Beaudrain method) and 2 m temporary surcharge;
- sand fill with ground water table lowering in vertical sand screens centre-to-centre 3 m (IFCO method);
- sand fill with ground water table lowering in vertical sand screens centre-to-centre 3 m (IFCO method) and 2 m temporary surcharge;
- EPS fill, designed to avoid loading the subsoil beyond the original stress;
- light weight volcanic ash fill with 2 m temporary surcharge;
- light weight volcanic ash fill with vertical band drains centre-to-centre 1 m;
- light weight volcanic ash fill with vertical band drains centre-to-centre 1 m and 2 m temporary surcharge;
- piled embankment on timber piles with load transfer platform;
- piled embankment on concrete piles with load transfer platform.

Post-construction settlements were determined for four lengths of time available for construction: 6, 12, 18 and 24 months. These time spans include 3 months for construction of the bridge abutment and the pavement. Especially the longer time spans are essential for the success of construction methods that induce soil settlement. Full consolidation and reduction of creep rates take time, but are required to keep post-construction settlements within acceptable limits. The time span of 6 months is in favour of methods that apply no additional load on the soft soil, such as an EPS fill and piled embankments.

Once the post-construction settlements are known the effect on life cycle cost depends on the length of the approach slabs and the type of road (figure 4). The approach slab is an expensive but widely used solution to keep the change in slope to a safe value. As a rule of thumb, the safe value is taken as the reciprocal value of the design speed in km/hour. So for a local road the maximum slope is 1/50, and 1/100 for highways. It follows that the allowable post-construction settlement at the far end of a 4 m approach slab for a highway bridge equals 4*1/100 = 0.040 m.

If the allowable slope is exceeded the ‘bump at the end of the bridge’ must be removed by reprofiling the pavement. The cost of this operation, including cost of traffic management, is assumed to be 70 €/m^2 of pavement. Also, it is assumed that after 0.25 m of post-construction settlement the entire approach slab is excavated and reconstructed. This major operation will disrupt traffic seriously; its cost are assumed as 220 €/m^2 of pavement.

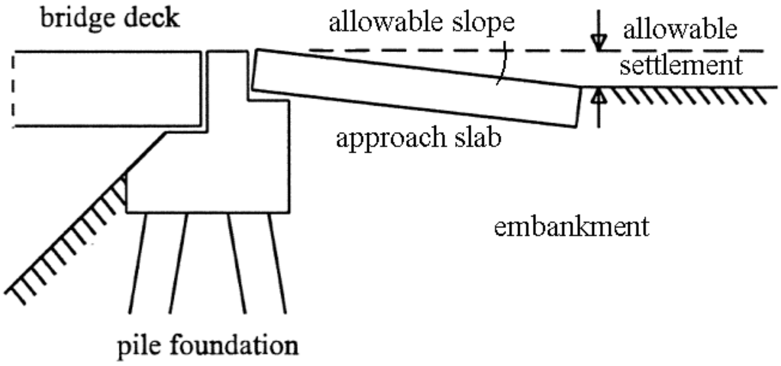

Figure 4 : Relation between allowable slope, length of approach slab and allowable settlement.

This model relates post-construction settlement and maintenance cost. For a given length of the approach slabs and an allowable slope, life cycle cost are defined as the sum of construction cost and the cost of all maintenance actions in the first 12 years after opening of the road.

SOME RESULTS OF THE LIFE CYCLE COST CALCULATIONS

The results of the life cycle cost calculations are best demonstrated by an example showing the effect of time available for construction on the selection of the construction method.

The first example is for a local road 0.4 m above ground level. The length of the approach slabs is 4 m; the maximum slope is 1/50. The life cycle cost are considered for the 8 soft soil profiles: two for peat, three for marine clay and three for fluviatile clay, and four construction methods:

- sand fill with vertical band drains centre-to-centre 1 m;
- accelerated loading method: sand fill with vertical band drains centre-to-centre 1 m and vacuum surcharging (Beaudrain method);
- piled embankment on timber piles with load transfer platform;
- EPS fill, designed to avoid loading the subsoil beyond the original stress.

Figure 5 presents the life cycle cost for a construction time of 6 months. The EPS fill turns out to be the most economical option for the 5 m peat profile and the fluviatile clay profiles. For the other soil profiles the accelerated loading method has slightly lower life cycle cost. Because the outcome of this method is more sensitive to variations in ground conditions than the EPS fill, it may be prudent to prefer the EPS fill. Piled embankments are reliable but significantly more expensive than the EPS fill. The excessive life cycle cost of the sand and band drains method are due to large post-construction settlements. Some designers may be tempted by the low construction cost of the sand and band drain method that are 40-70 % of those of the EPS fill. However, the life cycle costs are 3 to 10 times higher, depending on the soil profile. Figure 5 is an excellent example why decisions should be based on life cycle cost rather than on construction cost.

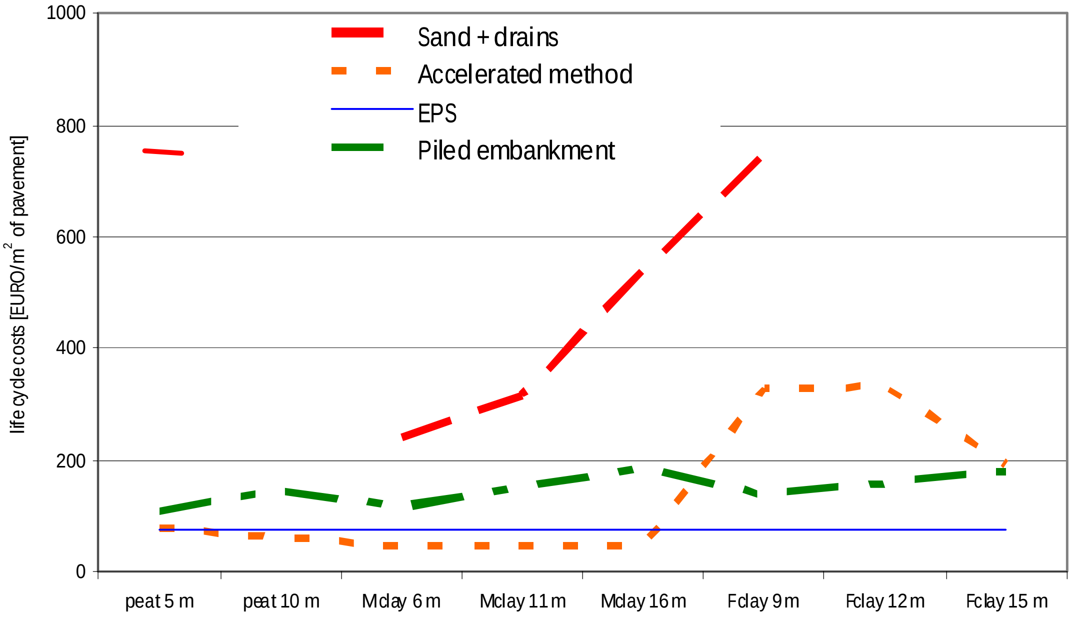

Figure 5 : Life cycle cost for different construction methods, local road GL+0.4 m, time available = 6 months.

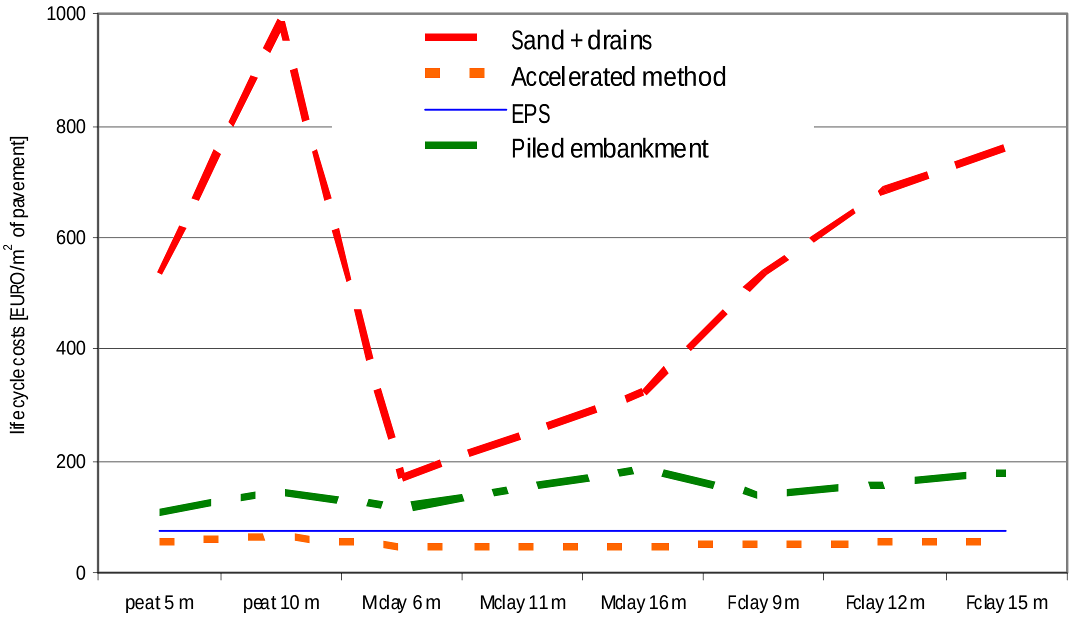

Figure 6 : Life cycle cost for different construction methods, local road GL+0.4 m, time available = 24 months.

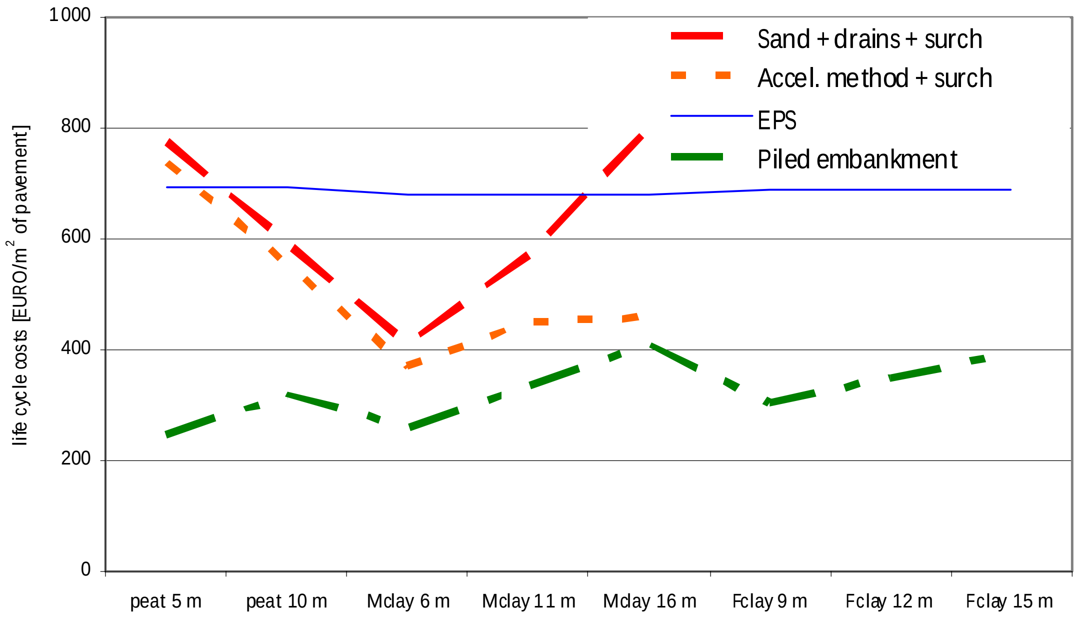

Figure 7 : Life cycle cost for different construction methods, highway GL+7.0 m, time available = 6 months.

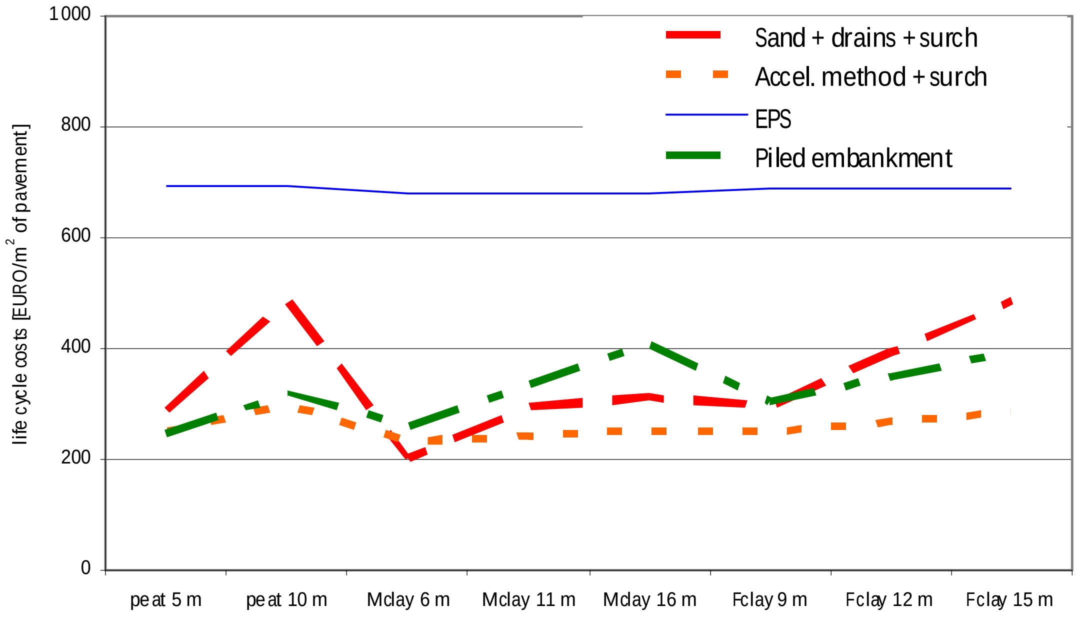

Figure 8 : Life cycle cost for different construction methods, highway GL+7.0 m, time available = 24 months.

Figure 6 gives the life cycle cost for a construction time of 24 months. The accelerated loading method is the most economical solution for all soil profiles. As stated before, an EPS fill may be preferred for its greater reliability.

The second example for a highway 7 m above ground level highlights the effect of embankment height. In both sand and band drain and the accelerated loading method a 2 m surcharge is added. Figure 7 gives the results for a construction time of 6 months. Life cycle cost of the sand and band drain and accelerated loading method are off the scale. A piled embankment is the most economical option for all soil profiles. The EPS fill is two to three times more expensive, because the costs of EPS are much higher than those of the sand fill used in the piled embankment. Figure 8 presents the results for a construction time of 24 months. In this case the accelerated loading method with surcharge and, for some soil profiles, the sand and band drain with surcharge methods are slightly more economical than the piled embankment. Again, a piled embankment may be preferred because of its greater robustness with respect to subsoil variation.

CONCLUSIONS AND RECOMMENDATIONS

Past and recent studies show that many factors contribute to the high maintenance cost of interfaces between bridges and embankments. The best way out of this situation is to make better use of the combined existing knowledge of geotechnical, structural and pavement engineers. Post-construction settlements of the embankment have been identified as the major cause of maintenance. The report of the CROW working group 'Effective bridge approach constructions' and the web tool 'Road Analysis Module – Bridge Approach Constructions' aim to present existing expert knowledge in easily accessible form for decision support of non-expert users.

Both CROW report and RAM-BAC suggest that an EPS fill is one of the most economical construction methods for embankments near bridges in low-lying roads. When considering the sensitivity of the accelerated loading method to subsoil uncertainty, an EPS fill is the safe choice. For higher embankments, piled embankments are more economical. An EPS fill will perform satisfactorily, but is more expensive.

Decisions on the construction method for bridge approach constructions must be based on life cycle cost, not on initial construction cost. The common sand and band drain method may appear cheap, but maintenance costs of the bridge approach construction are dramatic.

Future efforts should be directed primarily towards creating awareness among decision makers, implementing life cycle costing in contracting practice, and monitoring and evaluation of the performance of bridge approach constructions. Technological innovations in bridge approach constructions may be necessary for achieving extremely low maintenance constructions, such as jointless integral bridges, even in bad ground conditions.

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