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Integral design of motorways on soft soil on the basis of whole life costs

Conception intégrale des autoroutes sur sol mou selon le principe de coûts totals

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ABSTRACT
The Ministry of Transport has developed the decision support model MRoad for rapid design of pavements and embankments. MRoad predicts costs, construction time, effect on adjacent structures and roads and maintenance. This publication describes the interaction of the model with other tools used in motorway design. The relationship between functional requirements and requirements for geotechnical design is explained. The design process is illustrated by a case study for widening a motorway on soft soil. Considering costs and road capacity during construction, a piled embankment is the best choice. The presence of soft soil has a large effect on project costs.

RÉSUMÉ
Le Ministère du Transport a développé le modèle de soutien de décision MRoad pour la conception rapide des revêtements et remblais. MRoad prévoit des coûts, le temps de construction, effet sur les structures adjacentes et l'entretien de route. Cette publication décrit l'interaction du modèle avec d'autres outils utilisés dans la conception des autoroutes. Le rapport entre les conditions fonctionnelles et les conditions pour la conception géotechnique est expliqué. Le processus de conception est illustré par une étude de cas pour élargir une autoroute située sur sol mou. Considérant des coûts et la capacité de l'autoroute pendant la construction, un remblai empilé est le meilleur choix. La présence du sol mou a un grand effet sur les coûts de ce projet.

1 INTRODUCTION

Worldwide, scenarios for the future share the notion that mobility will be the backbone of continued economic growth. Facing congestion of current transportation networks, public and politicians demand instant solutions from governments with limited budgets for construction and maintenance. With the expansion of the road network in built-up areas, invading the remaining space often leads to conflicts of interests with other proprietors and legal limits for noise and air pollution. Soft soils and high groundwater tables further complicate construction and operation. Venmans (2003) summarises the challenges this situation presents to the geotechnical profession.

The Ministry of Transport (MoT) continuously searches for a balance between these expectations, requirements and constraints. A critical audience expects the effects of choices to be predicted and monitored. Practitioners in various disciplines cooperate to identify the complex relationships between functional requirements, technical requirements for pavements and embankments, technical solutions, legal constraints, natural conditions and costs.

Decision support models and expert systems are becoming an essential part of the toolbox. Barneveld and Venmans (1999) describe a decision support model for the selection of ground improvement methods for road embankments and widenings on soft soil. The model only considers technical requirements and initial costs. Venmans and Barneveld (2001) include costs for maintenance due to deformation of the embankment supporting the road and consider the effects of uncertainty.

The present paper describes the application of the decision support system MRoad in the process of motorway design, addressing the interaction with other disciplines. The relationship between functional requirements and requirements for geotechnical design is explained. The design process is illustrated by a case study for a road widening on soft soil, in which the feasibility of a piled embankment is investigated.

2 DESIGN PROCESS AND TOOLS

2.1 *Features of MRoad*

MRoad combines pavement design and geotechnical design for a motorway, calculating pavement thickness, settlements during operation, space required for stable slopes and damage to the existing road caused by the widening of the embankment. A future version will include the effect of ground deformations on nearby subsurface infrastructure and other objects.

Pavement maintenance is predicted by comparing calculated settlements to requirements related to safety and user comfort. The type of maintenance and its duration are inferred from expert rules. Initial and whole life costs can be analysed for comparison of alternative designs.

The core of MRoad is the twodimensional settlement calculation according to the a-b-c isotache model (Den Haan, 2000). MRoad shares this core and its possibilities for simulating ground improvement methods with MSettle, an application widely used in the Netherlands for settlement analysis (GeoDelft, 2005). Ground improvement methods in MRoad concern the installation of prefab vertical drains, use of temporary surcharges, vacuum consolidation (Beaudrain system), groundwater table lowering in sand screens (IFCO system) and lightweight construction using expanded polystyrene foam. The stability of slopes is verified by application of expert rules complied from many projects.

Pavement design is implemented by design charts relating the number of standard axle load passes to the thickness of typical asphalt and concrete pavements used in the Netherlands. MRoad includes unbound, lightly bound, hydraulically bound and cement bound road bases. Because most motorways have sand subbases thicker than 2 m, the geotechnical and pavement designs hardly affect each other and are treated independently.

MRoad derives the initial costs for a given design from volumes and lengths of building materials. The model predicts maintenance related to regular pavement replacement and repair, and maintenance for repair of damage caused by subsoil deformation. Maintenance costs are derived from an external source. Whole life costs are determined by combining initial costs with maintenance costs using the net present value method.

2.2 *Integration of MRoad in the design process*

MRoad works in close cooperation with other design models and decision support systems developed by the MoT (Fig. 1). Rather than joining different models into a single supermodel, the concept of individual dedicated models has been adopted. This approach least disrupts the current organization of work in the MoT and is flexible when models need to be modified. MRoad will typically be used for preliminary design, when detailed information on subsoil conditions is not yet available.

The following paragraphs describe the dependencies between the models; paragraph numbers refer to Fig. 1.

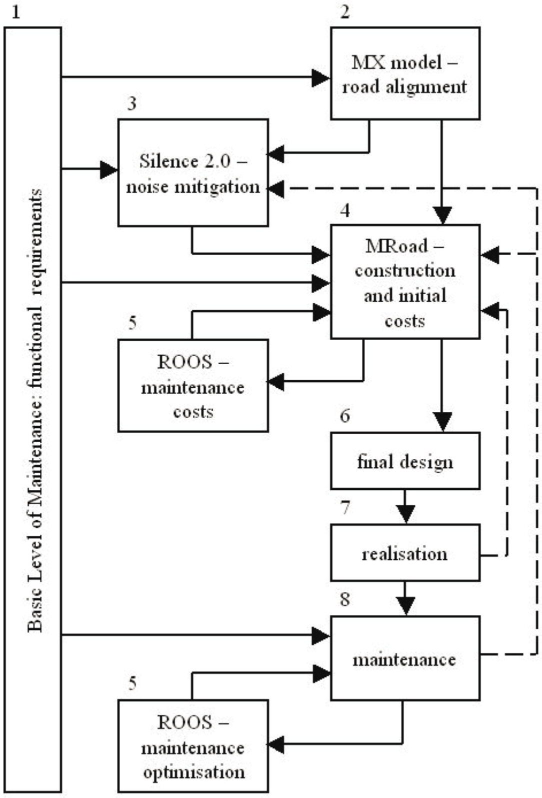

Figure 1. Integration of MRoad in the design process.

2.2.1 *Functional requirements*

The Basic Level of Maintenance of the MoT gives a set of functional requirements that describe the minimal condition of a road that a user may expect. Part of the requirements apply to the surface characteristics of the pavement. Subsoil related factors most directly affect requirements concerning longitudinal evenness, transverse slope and crack formation in the pavement. Although these functional requirements apply during operation of the road, the requirements must already be observed in the design phase.

2.2.2 *Design of road alignments*

Horizontal and vertical alignments of the road are designed for safe operation according to guidelines based on vehicle-road interaction, driver behaviour and traffic flow analyses. A first 3D model of the road and its surroundings is drafted in MX, the standard MoT CAD application used for producing drawings and constructing road geometry.

2.2.3 *Design of noise mitigation measures*

The determination of the future noise emission of the road is part of the environmental effect study. The MoT road noise model Silence 2.0 helps to design a combination of noise barriers and low noise pavement surface layers to keep noise nuisance within legal limits. The type of surface layer is an important input parameter for MRoad, because it determines the default pavement maintenance cycle. The type of surface layer has little effect on structural pavement thickness.

2.2.4 *Design of embankment and pavement construction*

MRoad is used in the preliminary design phase for a first assessment of the feasibility of the MX design with respect to available time, space and budget.

The main criterion in the selection of a ground improvement method is initial construction costs and additional maintenance induced by due to subsoil deformations. ‘Additional’ indicates that the maintenance is expected not to coincide with the default maintenance cycle for the given surface layer. Also, the direct costs of land procurement may be compared to costs for specific provisions allowing construction of steeper embankment slopes.

MRoad reads geometry data from the MX model, but changes to the MX model have to be made in MX. Subsoil data are obtained from MGeobase (GeoDelft, 2005).

2.2.5 *Design of maintenance*

The MoT has developed the application ROOS to optimise maintenance as to minimise traffic hindrance. At this point in the design process ROOS is used to estimate costs of maintenance. These costs concern regular maintenance resulting from pavement wear, additional maintenance to newly constructed pavements due to subsoil deformations and additional maintenance to existing pavements that are damaged during construction of a road widening.

2.2.6 *Final design*

The final geotechnical design will be made using the analytical design tools of DelftGeoSystems (GeoDelft, 2005) and the finite element package PLAXIS. These applications are the de facto standard for geotechnical design in the Netherlands. Continuity with the preliminary MRoad design is provided by the common soil data in MGeobase and the common soil models and algorithms. In the next years, also PLAXIS will be integrated in the DelftGeoSystem tools.

2.2.7 *Realization*

Monitoring data collected during construction of the road embankment may be used to calibrate soil properties in MGeobase for future design with MRoad.

2.2.8 *Operation and maintenance*

Every two years the condition of the entire motorway network is measured and compared to the functional requirements. The data is used to evaluate the remaining service life of the pavement, predict maintenance and optimise maintenance operations for larger sections of the motorway, using ROOS. The calibrated information on service life of the pavement is entered as expert knowledge in Silence 2.0 and MRoad.

3 RELATING FUNCTIONAL REQUIREMENTS TO REQUIREMENTS FOR GEOTECHNICAL DESIGN

3.1 *Functional requirements for motorways*

The key to predicting maintenance is a one-to-one translation of deformations of the embankment to changes in the road surface geometry. Functional requirements define the road surface geometry that is marginally acceptable from the viewpoint of safety and user comfort. The initial road surface geometry is affected by changes in elevation, slope and curvature of the pavement, which are controlled by horizontal and vertical deformations of the embankment. Although the accuracy of the relationships implemented in the current version of MRoad needs to be improved upon, the approach described in this chapter seems promising.

Relevant functional requirements for pavements on newly constructed embankments are as follows:

1. Height differences in longitudinal direction shall not exceed 0.05 m over 25 m (related to user comfort).
2. The transverse slope shall be between 1 % and 5 % in straight sections of the road. In curves, other limits apply (related to safety).
3. Cracks in the pavement shall be less than 20 mm in width, the height difference over the crack not exceeding 10 mm (related to safety).
4. The embankment shall have sufficient stability (related to safety).
5. The longitudinal slope near transitions from embankment to rigid structures shall not change more than 1 % (related to safety).
6. Rutting as a result of pavement failure after freezing and thawing of the road base shall not occur (related to safety, economy).

The first four requirements also apply to existing pavements subject to deformations caused by widening the embankment.

The translation of the last three functional requirements to requirements for geotechnical design is relatively straightforward. Venmans and Barneveld (2001) present an optimisation scheme for the design of transitions from embankments to rigid structures. The first three requirements may be analysed by considering changes in elevation, transverse slope and curvature of the pavement. By comparing the development of these quantities in time with the corresponding requirements, the time can be identified when pavement geometry or integrity must be restored by maintenance.

3.2 *Requirements for geotechnical design related to height differences in longitudinal direction*

Several natural and manmade features may cause differential changes in elevation in longitudinal direction:

1. The road may pass into an area where the subsoil has a different loading history, e.g. caused by fills, road or river embankments, or temporary roads. These changes may occur over short distances.
2. The road may pass over soil that is heterogeneous at a large scale, caused by the presence of sediments with different compressibility. Channel fills and overbank deposits are typical features found in deltaic environments that may be reflected in the longitudinal road profile.
3. The road may cross ditches, where the weight of the fill in the ditch differs from that on the surrounding soil.
4. Small-scale soil heterogeneity, caused by differences in compressibility and thickness of soil layers otherwise considered as homogeneous on the basis of a routine soil investigation.

The first three features should be easily detected in a proper site investigation. Since dimensions of large-scale heterogeneities may be as small as 25 m, the standard Dutch site investigation scheme should be complemented by a geological desktop study.

MRoad evaluates the effects of differences in preload and large-scale heterogeneity on height differences by directly comparing time-settlement diagrams for representative soil profiles at both sides of a transition. The effect of ditches is calculated on the basis of semi-empirical design rules, considering the effects of dimensions of the ditch relative to the thickness of the compressible layers, absolute settlement and remedial measures.

Small-scale heterogeneity is considered an intrinsic characteristic of soft soils and needs not to be mapped in detail. Its effect is assessed on the basis of the empirical observation that absolute settlements in a virtually homogeneous area may vary by 30 % over distances in the order of 25 m. It can be shown that in this case differential settlements after construction are approximately one third of the absolute settlement after construction. Since the latter can be calculated, also the height differences are known.

3.3 *Requirements for geotechnical design related to transverse slope and crack formation*

The determination of the development in time of the transverse slope and curvature of the pavement from a settlement calculation is straightforward. Both quantities may become critical in case an existing embankment on soft soil is widened. A settlement calculation ignores the effects of horizontal deformation and interaction of pavement, embankment and subsoil. Because MRoad is meant for preliminary design, this simplified approach may be sufficient. Also, it is felt that the calibration of more sophisticated design models against field data in this particular field is light-years behind recent developments in computing power, limiting the value of the predictions made with these models. However, future versions of MRoad may see the implementation of expert knowledge based both on finite element calculations and field observations.

4 CASE STUDY: ROAD WIDENING IN AN INDUSTRIAL AREA

4.1 *Situation*

This case study concerns the widening of a motorway located in the centre of the Netherlands. Although the case is fictive, technical details and cost figures are realistic.

The present 2x2 lane motorway connects two major intersections and passes through a industrial area with scattered residences. In order to increase its capacity the motorway will be reconstructed to carry 4x2 lanes. The 3 km project must be realized in a short time span, with minimal reduction of road capacity during construction and minimal future maintenance.

The embankment carrying the new lanes is to be built on a 5 m layer of highly organic soft soil. At a sort distance from the existing road, two large diameter water conduits are present supplying water to a major city. Relocation of the conduits is very expensive and should be avoided.

4.2 *Reference design*

The existing road dictates the alignment of the new lanes. The 'standard' guidelines are adopted for the distances between the lanes and slopes of pavements and embankment (Fig. 2).

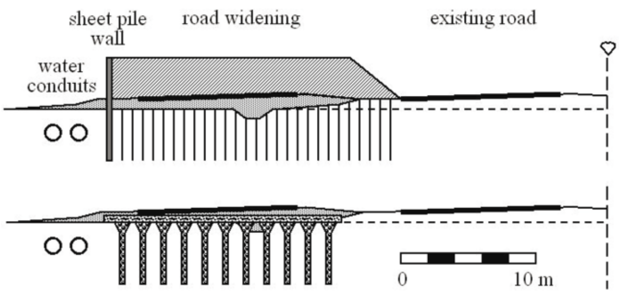

Figure 2. Cross sections of west half of the motorway, with reference design (top) and alternative design (bottom).

The current policy of the MoT dictates that porous asphalt is to be applied to reduce noise emission and splash and spray. An analysis of noise emission with Silence 2.0 reveals that noise barriers will need to be constructed over 15 % of the length of the project in order to meet legal limits.

The default maintenance scheme for porous asphalt on 2 lane roads implies treating the fast lane for loss of aggregate after 10 years and completely replacing the surface layer after 14 years.

The initial geotechnical design by MRoad indicates that 3 m of fill is required to construct the 1 m embankment, and that settlements during operation of the road will be 0.40 m. As a result, longitudinal evenness will reach unacceptable values after 3 years because of small-scale and large-scale variability of the subsoil. By adding a 1 m temporary surcharge settlements during operation are reduced to insignificant values.

Settlement of the widening is expected to cause severe damage to the existing pavement. After one month the transverse slope of the emergency lane will exceed the required value. Cracks will start to appear after 2 months. The transverse slope and crack formation of the fast lane will only just meet the requirements. The extent of the damage is such that 50 % of the pavement will need to be replaced over its full depth after removal of the temporary surcharge. Because repairing the emergency lane is not feasible during construction of the widening, a barrier has to be placed between the damaged emergency lane and traffic. The width of the remaining lanes must be reduced to accommodate this barrier, and the allowable speed lowered. The reduction of road capacity will lead to considerable congestion.

Lateral ground deformations will cause unacceptable deformation and possible failure of the water conduits west of the road. A 12 m sheet pile wall is installed for protection.

Widening the east side of the road will proceed in a similar way, but without the sheet pile wall. On both sides of the road, traffic is redirected temporarily over the new pavement during reconstruction of the existing pavement. The total time required for reconstruction of the motorway is 15 months. The default maintenance scheme is not affected by subsoil related factors.

4.3 *Alternative design*

The alternative design for the west part of the road implies construction of a load transfer platform (LTP) supported by AuGeo piles (Fig. 2). AuGeo piles consist of foamed concrete poured in a plastic casing that is pushed into the ground by a drain stitcher. The top of the pile is reinforced and the pile head is enlarged. The bearing capacity of a 150 mm diameter pile is in the order of 150 kN. The LTP consists of crushed stone reinforced by 2 layers of geogrid.

Settlements and lateral deformations of this solution are virtually nil and additional measures to prevent damage to the existing pavement or water conduits are not required. After completion of the new pavement only the surface layer of the existing pavement is replaced.

The widening on the east side will entail the placement of prefab vertical drains and a sand fill. In the alternative design the temporary surcharge is replaced by vacuum consolidation using the Beaudrain system in order to limit construction time.

The advantage of this method is the reduction of residual settlements to acceptable values within 6 months, with moderate additional costs. The disadvantage is an increase in damage to the existing road. For this reason the road will be taken out of operation during consolidation of the widening on the east side by temporarily diverting traffic over the 2x2 west lanes after their completion. The reduction of road capacity is limited, since at all times the full width of the lanes is available.

The total time for construction in the alternative design will amount to 13 months. As in the reference design, maintenance will depend only on deterioration of the porous asphalt, not on subsoil related causes.

Table 1: Cost breakdown of embankment and pavement (x1000 €)

Item	Reference design West	Reference design East	Alternative design West	Alternative design East
LTP + AuGeo piles	0	0	4700	0
drains and sand fill	1900	1900	0	0
Beaudrain and sand fill	0	0	0	2800
New pavement	1300	1300	1300	1300
Reconstruction of existing pavement	750	750	150	750
Sheet pile wall	1200	0	0	0
Traffic management	800	800	150	50
Total	5950	4750	6300	4900

4.4 *Comparison of designs*

Table 1 gives a breakdown of costs related to embankment and pavement construction in both designs, for 3 km of motorway.

The costs related to embankment and pavement construction are 10.7 M€ for the reference design and 11.2 M€ for the alternative design. Whole life costs need not be considered because maintenance is the same in both designs. Additional costs in both designs, for instance costs of noise barriers and traffic handling systems, amount to 5.7 M€. A 75 % supplement for engineering, contract management and VAT, and 5.1 M€ for land procurement brings total project costs to 33.8 M€ for the reference design, and 34.7 M€ for the alternative design. Since the costs for a similar project built on a firm subsoil would be 22.5 M€, the soft subsoil increases project costs by about 50 %.

In spite of the slightly higher costs the alternative design will probably be preferred because congestion during construction is substantially less than in the reference design.

5 CONCLUSIONS

Decision support models have become a necessity in the complex environment surrounding the realisation of Dutch motorways in built-up areas. Unfavourable subsoil conditions may cause a substantial increase in project costs. The decision support model MRoad allows a rapid evaluation of embankment and pavement designs for costs, construction time and effects on adjacent pavements and structures. MRoad is a useful addition to the designers toolbox.

The key to predicting maintenance caused by subsoil conditions is relating functional requirements for pavement geometry and integrity to requirements for geotechnical design.

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