Development of an Advanced Control System for Shield Tunnelling Machines

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Abstract

This paper describes the development of a control system for shield tunnelling machines. The purpose of this control system is to avoid soil stress reductions during the shield tunnelling process that are due to sub optimal machine control. In the current situation, this sub optimal control can occur because the machine operator can not take all relevant information into account. E.g. he can not anticipate to local changes in soil conditions around the tunnelling machine nor can he observe settlements at the surface to optimise control actions.

This paper describes an idea and plan to develop a new type of control system. With the help of computer modelling and simulation it should become possible for the operator to evaluate his control actions in a simulation before he takes them. This way control actions can be optimised in an iterative procedure. Measurements of surface settlements are to be used to evaluate the simulation with the 'as realised' situation.

1 Introduction

Due to increased urbanisation and traffic intensities in the Netherlands, there is an increasing demand for tunnels for underground roads and railway lines. As a side effect of this increased urbanisation, it is becoming less acceptable to use conventional open pit construction methods for the construction of tunnels. The solution to this problem is believed to be the use of mechanised shield tunnelling techniques. In many countries mechanised shield tunnelling is being used successfully for many years. However in The Netherlands the first mechanised shield tunnelling project has started at the beginning of 1997. The unstable Dutch soil is believed to make shield tunnelling a complicated matter.

The Dutch government has decided that it is of national benefit that experience is gained with the shield tunnelling technique. Therefore a public private partnership was started that is called Centre for Underground Construction (COB). This centre co-ordinates a multi million national R&D program to obtain know-how and experience in shield tunnelling. In parallel to this national R&D program, a number of shield tunnelling projects is initiated. The first project is the construction of the second Heinenoord tunnel, south of Rotterdam. A R&D project is organised to measure all relevant phenomena and process parameters taking place in the tunnelling machine as well as in the environment of the tunnel. The purpose of these measurements is to verify predictions made about the tunnel design and construction aspects in order to obtain understanding of the shield tunnelling method.

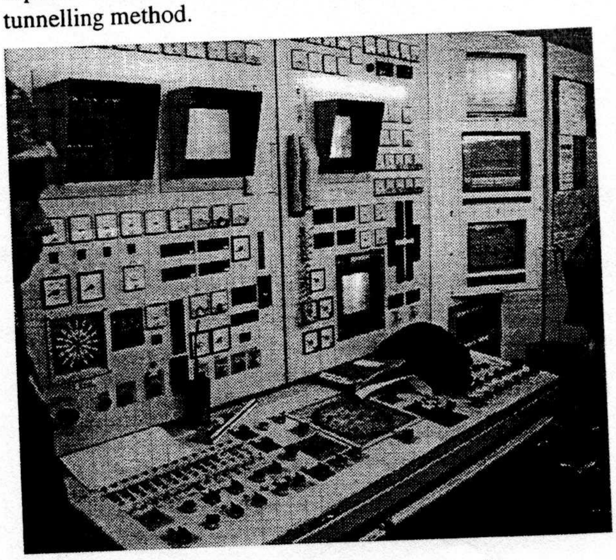

Figure 1 *Image of shield tunnelling machine operator control panel*

Within the above mentioned national R&D program a special project has been initiated that aims at the development of a new generation control system for shield tunnelling machines. This new generation control system has the purpose to improve the performance of the tunnelling process by decreasing the reduction of soil stresses caused by the tunnelling machine. Such a new generation of control systems has been called an Advanced Tunnelling machine Control System (ATCS). This paper describes the plans and objectives of a research project that aims at the development of such an ATCS.

This paper is divided into eight sections, of which this introduction is the first. The outline of the rest of this paper is: 2. Research Objectives, 3. Problem Analysis, 4. Requirements for an ATCS, 5. Previous and Related Research, 6. A Concept for an ATCS, 7. A Plan for the Development of an ATCS, 8. Conclusions.

2 Research Objectives

In the current generation shield tunnelling machines it is unavoidable that some soil stress relief and disturbance of the soil around the machine and the tunnel occurs. Relief is primarily caused by the so called *loss of volume* which occurs because the shield tunnelling machine tends to excavate more soil than the volume of the tunnel that is built. Typical values for the loss of volume are 0.5% to 3% of the tunnel volume.

The loss of volume is partly inherent to the machine design, and partly caused by sub optimal machine control. The relief of soil stresses causes stress dislocations in the ground and settlements at the surface.

The purpose of an ATCS is to improve the control of the various shield tunnelling machine processes such that loss of volume and stress dislocations in the ground is avoided. The benefits of improved machine control are:

- It becomes possible to construct tunnels closer to building foundations without affecting their load bearing capacity, therefore limiting the risk of damage to those buildings. Money can be saved on precaution measures such as ground stabilisation or foundation modifications.
- Tunnels can be constructed closer to the ground surface without risking unacceptable surface displacements. The closer to the surface the shield tunnelling machine can start, the less expensive the tunnel entrances are.
- The tunnelling progress speed can be increased when risks for damages are low.

The above mentioned benefits can save large amounts of money, but they also contribute to enlarge the area of application of the shield tunnelling technology for the construction of tunnels in urban areas because the limits of 'what is possible' are shifted.

3 Problem Analysis

In the current state-off-the-art shield tunnelling all tunnelling machine processes are controlled by the operator in the machine. (Figure 1 shows the control panel of a shield tunnelling machine.) The feedback information that is used to control the tunnelling machine, is limited to phenomena measured inside the machine. Soil stress relief and stress dislocations are not fed back to the operator. Nevertheless the operator is requested to minimise soil stress relief.

The functionality that is required of an ATCS is to control the tunnelling machine sub systems in such a manner that relief is minimised. In order to explain the idea how this can be realised, it is necessary to understand which functionality is fulfilled by the various systems of a shield tunnelling machine. Subsection 3.1 introduces some relevant concepts of shield tunnelling. Subsection 3.2 discusses the problem of controlling the tunnelling machine processes.

3.1 Shield Tunnelling

The functionality that can be found in most shield tunnelling machines is similar. The primary functions in a tunnelling machine are (see Figure 2):

1. Excavation of soil at the machine face.
2. Transportation of excavated soil
3. Temporary support of soil and ground water, both at the face, and at the machine skin
4. Construction of the tunnel lining

Below, a short (simplified) explanation is given how each of the above functions is fulfilled.

Excavation

The soil at the face of the tunnelling machine is excavated by a rotating wheel which is equipped with cutting teeth. The propulsion of the machine is achieved using hydraulic cylinders which push the machine forward against the assembled lining. The direction of excavation

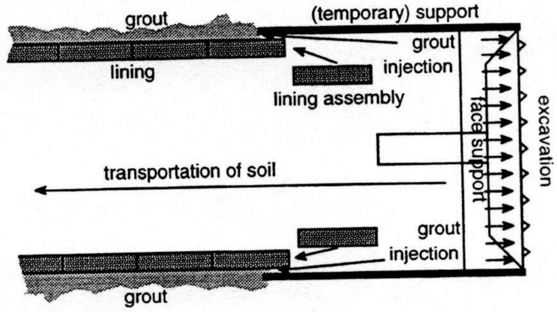

Figure 2 Functions in shield tunnelling machine

can be controlled through variation of the propulsion forces at different sides of the machine.

Transportation

Alternative transportation systems are being used in various tunnelling machine designs. In The Netherlands, the so called *slurry shield* tunnelling machines are used. In a slurry shield machine, a fluid of bentonite mixture is used to transport the excavated soil as a slurry through pipes. In a separation plant the excavated ground is filtered out of the slurry. The bentonite is than pumped back to the excavation chamber.

Temporary support

In the chamber at the front of the machine a retaining pressure is maintained to support the excavation face in front of the excavation wheel. A complication in the fulfilment of the face support function is that the properties of the slurry in the excavation chamber influence the performance of the face support. Therefore there are interactions between the transportation system, the separation system and the face support.

Another aspect of the temporary support, is the ground support at the machine skin. In tunnel curves the cylindrical machine has to force itself through the curve causing extra soil stress relief and stress dislocation. (See Figure 3)

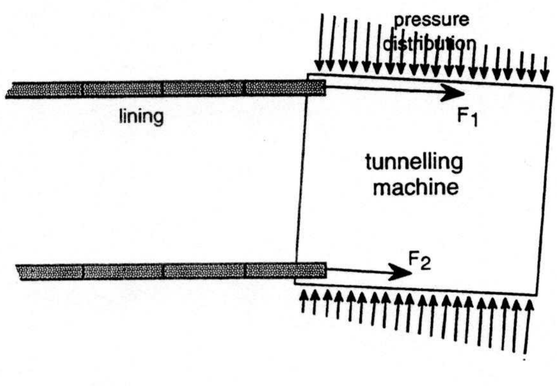

Figure 3 *Soil stress relief caused by directional changes of the tunnelling machine*

Construction of Tunnel

Prefabricated concrete segments are assembled to rings which form the tunnel lining. This lining is assembled within the tunnelling machine and has a slightly smaller diameter than the tunnelling machine. This causes a so called *annular void* to be created. This annular void is injected with grout to avoid stress relief as the machine progresses.

The control of the grout injection volume and pressure are dependant on the progress of the machine and the type of ground near the annular void. The less compact the ground is the more grout is needed.

A comprehensive overview and explanation of shield tunnelling technology can be found in [6].

3.2 Shield Tunnelling Machine Control

A direct and effective method to avoid ground stress relief would be to measure the soil stresses and feed these measurements back to the operator. The problem with this strategy is that it is practically impossible to measure stress relief around the tunnelling machine. Related effects such as surface settlements can be measured more easily. The first problem by using surface settlement data is the significant time delay between the moment of stress relief and the moment at which surface settlements can be observed. In other words, when surface settlements occurs, it generally is too late to take actions. (Assuming that the occurrence has something to do with changing conditions). A second problem is that it is difficult to establish a relation between the observed settlement and a cause of stress relief (i.e. face support problem, direction change, void injection problem).

The only way that surface settlement measurements can be used in the tunnelling machine control, is to verify the anticipated effects of control actions before giving them. In order to be able to predict the effects of control actions, it is necessary to understand what is happening and capture this in a simulation model which can be used to predict the effects of control actions.

No model is of value without the correct model parameter values. The behaviour of the local soil due to the tunnelling machine processes is very difficult to predict. There are two reasons for this:

1. The local ground conditions around the tunnelling machine are not known in full detail. (What kind of soil is to be dealt with?)
2. The behaviour of soil can only be predicted with a limited accurately,

As a consequence, the reaction of the soil on a tunnelling machine can be uncertain when ground conditions vary frequently. In the current method of tunnelling machine control, the operator has no accurate information about local ground conditions around the tunnelling machine. Therefore he can only react to these changes and never anticipate. The operator can only observe changes in ground conditions form the changes in behaviour of the tunnelling machine.

A complication for tunnelling machine control is that most tunnelling machine processes have mutual interactions. E.g. when the excavation progress is changed, there are consequences for the amount of bentonite slurry that is needed, and the amount of grout that needs to be injected into the annular void.

4 Requirements for an ATCS

In order to minimise volume loss it is essential that the tunnelling machine systems which interact with the ground around the tunnelling machine are controlled in such a manner that they support the ground pressure as good as possible. Due to the unstable nature of the soil in the Netherlands, short periods of insufficient ground support will lead to irreversible ground settlements resulting in damage to buildings.

This objective can only be realised when all tunnelling machine subsystems are control by one integrated system which is aware of the interactions between the various tunnelling machine subsystems, such as there are:

1. the excavation system at the tunnelling machine front
2. the transportation system that regulates the retaining pressure in the excavation chamber
3. the steering system to avoid unnecessary loss of ground support at the side of the tunnelling machine
4. the injection of grout at the tunnelling machine tail that supports the ground around the lining or in case of a tunnelling machine that constructs an extrusion lining, the extrusion lining production system

Feed back from the environment of the tunnelling machine (i.e. from the surface) is to be used in the ATCS control strategy to be able to minimise stress relief. This idea is shown in the $IDEF_0$ diagram in Figure 4.

A problem of feed back of surface settlement observations into the control of the tunnelling machine, is the possibility of a significant time delay between soil stress relief caused by the tunnelling machine and a settlement at the surface. Such delays should not have a negative effect on the ATCS performance.

5 Related and Previous Research

In many conference proceedings publications can be found about tunnelling machine control. The amount of publications originating from Japan subscribe the leading role of that country. Control systems that are now used in nearly all large diameter shield tunnelling machines are *direction control systems*. Various publications, including [3-5, 8-11] describe such systems. Direction control systems are an essential part in an ATCS to avoid unnecessary direction changes when possible.

Due to shortages in skilled personnel, Japanese contractors have been working on more advanced automatic control systems for tunnelling machines. The first publication on this subject originates from 1984 [2]. The approach followed in several Japanese developments (e.g. [7] and [14]) aims at the replacement of the tunnelling machine operator by an expert system or fuzzy logic. In only a few publications ([1] and [12, 13]) it is mentioned that external measurements (i.e. surface settlement, earth pressure) are used for tunnelling machine control. A special research project in France is described in [12]. In this project a control system for shield tunnelling machines called 'CAP' is being extended. The CAP system has already been used in at least 18 tunnelling projects. The CAP system however is primarily a direction control system, and does not (yet) include observations outside the tunnelling machine in the control strategy.

A method that is sometimes used to eliminate surface settlements is to inject such amounts of grout in the annular void, that any settlements caused by the machine excavation process are undone. However, such a settlement correction process does not prevent damage to buildings close by the tunnel and therefore does not substitute the need for an ATCS.

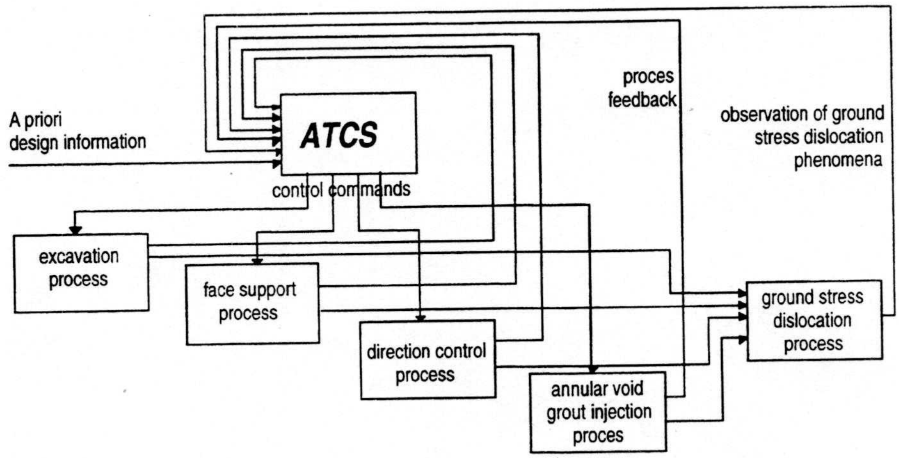

Figure 4 *$IDEF_0$ diagram of processes and information flows*

None of the publications seem to use computer simulation techniques in the control system to anticipate to variations in ground conditions or optimise control actions for a minimum relief of soil stresses. Nevertheless there are no reasons to start from scratch in the development of an ATCS. There exists many essential components that are needed in an ATCS.

6 A Concept for an ATCS

The concept of the proposed ATCS design is to control the tunnelling machine functionality from a ground settlement and soil stress relief control point-of-view instead of controlling the tunnelling machine systems individually.

The following techniques are envisioned to be used in the ATCS (See Figure 5):

1. The system uses sensing systems such as ground penetrating radar and horizontal penetration tests for observation of local soil conditions in front of the tunnelling machine. This way as much as possible 'a priori' information is obtained.
2. The ATCS uses computer simulation models to predict ground settlement reactions to control actions.
3. The ATCS uses feedback of surface settlement measurement systems to optimise its control strategy by compensation of deviations between predicted settlement reactions and measured reactions.

The use of a computer prediction model is an important ingredient of the proposed system design. The prediction model enables the consequences of control actions to be evaluated before they are actually performed. This requires that the prediction model matches the actual soil behaviour. For that it is necessary to have: (1) knowledge of soil behaviour in general. (2) accurate information about the characteristics of the local soil around the tunnelling machine.

In several related research projects, also co-ordinated by the COB, these problems are dealt with. One project is investigating the use of new ground reconnaissance methods such a ground penetrating radar and horizontal penetration tests. These techniques will be used to establish what the local soil conditions in front of the tunnelling machine are. In other projects the behaviour of soil in various conditions is being examined.

7 Research Plan

As mentioned in the introduction of this paper, a research project has been initiated for the development of an ATCS. Within this project three phases are distinguished:

1. A specification phase where the requirements for the ATCS are formulated in detail, the feasibility is evaluated and a conceptual design is drawn up.
2. A research and development phase where the required know-how for the implementation of a prototype ATCS is obtained
3. An implementation phase where a prototype ATCS is implemented and tested in a tunnelling project.

In March 1997 the first phase was started. A consortium of engineering consultants and R&D organisations is responsible for the first phase.

After the establishment of the feasibility of an ATCS, the research project continues and tunnelling machine manufacturers and contractors will be asked to participate in the project.

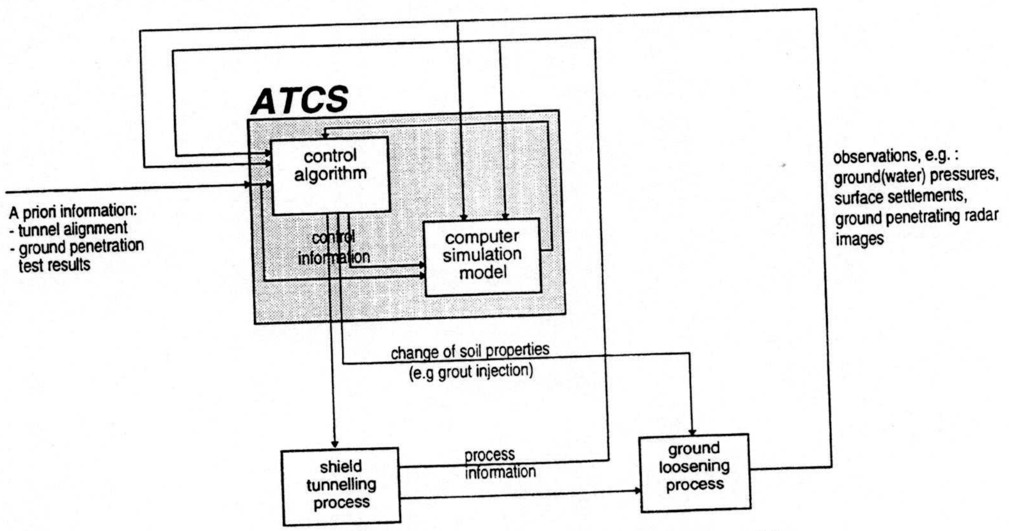

Figure 5 Idef0 diagram of information flows in ATCS controlled tunnelling machine

8 Conclusions

The development of an Advances Tunnelling machine Control System is an ambitious goal. It is believed that the formulated project goal is feasible one. Innovative aspects of the project objective are: (1) to incorporate ground behaviour prediction models into the system to analyse the effects of control actions, (2) to include surface settlement observations to fine adjust the prediction models.

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