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CATSBY: Collapse real-time prevention system for slurry tunnel boring machines in soft ground

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ABSTRACT : For slurry shield tunnel boring machines in soft soils, the Bouygues' Signal Aided Boring concept (CATSBY system, for Creusement Assisté par Traitement du Signal - BouYgues) has demonstrated its ability not only to automatically detect microcollapses at the tunnel face (alarm signals) but also to anticipate the emergence of favourable conditions to their occurrence (risk level variation indicators). This paper describes the basic principles on which Signal Aided Boring is based, and the experiments carried out on two tunnels to develop this concept. *NB : CATSBY is a Bouygues' registered trade mark*

1- INTRODUCTION

An increasing number of tunnels are built, or planned to be built, in urban areas, at shallow depths, or nearly existing structures (foundations, underground, transport infrastructures, sewers, etc.).

Among these, an also increasing proportion is, or will be completed using Tunnel Boring Machines (TBM), due not only to cost and planning considerations, but also to their lesser impact on the environment.

The efficiency of the technique has been greatly improved during the last years, thanks to machines' improvements, developments in confinement materials and monitoring, and also to the experience enhanced by specialised teams which have been involved in several projects regarding various contexts.

However, TBMs still remain almost blind machines, which have generally to be stopped, or, at least, slowed, if one wants to get information on the geotechnical conditions around the TBM, and at the face vicinity. Unless accepting a systematic low advance rate, these techniques can only be used when and/or where specific risks are feared. Except in precise areas, where problems are expected for obvious reasons (evidence of a fault, existing human-made structures or holes...), it is impossible to optimise the balance between advance rate and safety.

This urged Bouygues to decide to develop a method, able to detect any change in the geotechnical context which could increase the probability to collapse, without any impact on the production (boring and segment erections) sequence and timing.

This led us to the Signal Aided Boring Concept (or CATSBY system), which was first experienced, a posteriori, on two sites in France, and which will is going to be tested in full scale and real time conditions in 1996.

2 - REAL-TIME DETECTION STRATEGY

2.1 - Basic Principles

A major collapse at the tunnel face appearing during boring (or with a lag depending on the geotechnical conditions) is the result of the propagation of one (or several) 'microcollapse' (s) occurring at the tunnel face vicinity (and generally near the tunnel crown).

Therefore, a major collapse can only occur if the two following conditions are both fulfilled:

- occurrence of a microcollapse near the tunnel crown,
- possibility for this collapse to spread up to surface layers or existing foundations..

The first condition is due to inadequate confinement conditions, that is either an insufficient confinement pressure for the actual soil strength and water level, or too poor slurry rheological property for the actual soil porosity and permeability. If one assumes that the relation between soil characteristics and adequate confinement parameters is known, a microcollapse may therefore be considered as due to an overestimation of local soil characteristics.

This overestimation may be systematic within a given geological layer, in this case microcollapses will happen very frequently (with possibilities of interacting altogether, increasing the probability for greater local collapses). However, in most cases, it is only local, since the microcollapse occurs just where the soil strength is low or its permeability high, compared to the a priori estimated conservative values.

The second condition is bound to local geotechnical properties not only just around the tunnel, but also of the upper layers. If these are strong enough, they may be able to stop the collapse propagation thanks to arching effects. However, if a natural or artificial weak area exists above the initial microcollapse, it enhances this collapse spreading. It is also connected with the quality of injections behind the lining, which is another subject.

2.2 - Development Strategy

As the second condition is a function of soil parameters within the whole volume between the tunnel and the soil surface, it is almost impossible to deduce, from the tunnel boring parameters, if the geotechnical context is favourable, or not, to collapse spreading towards the surface. Moreover, it is always better to detect a problem at its origin rather than after it has grown.

Therefore, when developing CATSBY system, we focused on the detection of microcollapses. To be more precise, we worked on two complementary objectives :

- immediate detection of microcollapses events by adequate "warning signals", in order to adapt the injection behind the lining and, in case of repeated alarms, the confinement parameters;

- anticipation of risk areas by adequate "indicators", representative of the interaction between the TBM and the surrounding soil.

For each of these two objectives, we analysed signals measured by two TBMs recently operated by Bouygues in France. Considering both the results of these analyses and the observed events during boring, we were able to develop the warning signals and indicators presented in sections 3 and 4.

2.3 - Experimental Tunnels

2.3.1 - Strasbourg Tramway

The 8.9 m diameter tunnel was bored in coarse, more or less sandy, gravel, with an air bubble slurry pressure Herrenknecht TBM. The thickness between the tunnel crown and the surface was roughly between two and three diameters. The maximum surface settlements were 5 mm, and this objective was achieved, except in two localised loose areas, a priori impossible to know, where collapses occured and reached the surface.

The tapes containing the monitored data were only partially analysed, due to the huge amount of data, and to the fact that the software had not been designed for such a back analysis. However, it was possible to analyse two sections of about 100 m long each. The first one corresponded to relatively good soil conditions; the second one to poorer geotechnical conditions (loose or highly permeable areas), where problems actually occurred.

Although it was partial, this experiment led us to the first concepts of our system: warning alarms based on signal fluctuations, and indicators based on average values of more global parameters representing the interaction between TBM and soil.

2.3.2 - Clichy - La Briche Sewer

This 2250 m long sewer, located in a suburb of Paris, was also bored with an air bubble slurry pressure Herrenknecht TBM. Its outer diameter is 3.75 m, and the relative tunnel depth (cover height / diameter) is much more important than in the previous case.

The geological profile, along the tunnel axis, was composed of two main parts:

- In the first one (800 m long), the tunnel was bored in Marnes et Caillasses (marls and gravels), with natural fontis (caves) areas, due to gypsum dissolution, which led to very permeable areas with blocks contained in a silty-sandy matrix. The risk for collapses was found to be very important in this area. As a matter of fact, two events were noted: a collapse (ring 159), which made the works stop for several days; a brutal loss of slurry at the face (ring 204), due to the fact that the face intersected a highly permeable area created by dissolution.
- In the second one (more than 1000 m), it was bored in clayey sands (Sables de Beauchamp). No major incident occurred in this area.

3 - ALARM SIGNALS

3.1 - Basic concepts

As explained above, microcollapses may constitute adequate alarm signals, for either they represent the first phase of a more important collapse, or they are an indicator of the fact that the stability around the excavation is not perfect, with present geotechnical and confinement conditions.

As microcollapses cannot be detected directly, one must investigate methods able to detect their impact on the TBM's behaviour. If one considers that a sudden microcollapse systematically involves fluctuations around the ideal steady state corresponding to regular excavations with constant confinement, it is likely that the standard deviation of some TBM parameters can constitute reliable alarm signals.

3.2 - Strasbourg experiment

This idea was first tested on the Strasbourg tunnel, by comparison of different types of numerical computed signals with actual geology and incidents. It led us to the conclusion that the standard deviations of air bubble pressure (P) and of the slurry level, within the TBM chamber (h), appeared to be representative of the risk level (rather than fluctuations of such parameters like the wheel rotating power for instance).

The standard deviations σ_P and σ_h were computed for a 3 minutes period for each ring, with a sampling frequency of 5 Hz. For technical and practical reasons (among which the huge amount of data to be treated a posteriori), these 3 minute periods were arbitrarily chosen, for each ring, during boring operations.

In order to check these first conclusions in the most objective way, it was decided to proceed, on the second experimented site, to the direct computation of σ_P and σ_h on the whole length where monitored data were available, and to analyse the so obtained diagrams.

3.3 - Clichy la Briche experiment

From the comparison between these alarm signals levels and actual conditions (geology, observed collapses, injection volumes, incidents related by the pilots...), we could draw the following conclusions.

As for Strasbourg tunnel, the occurrence frequency, and the order of magnitude of these alarm signals, were largely higher for the sections considered (both a priori and a posteriori) as the poorest considering geological contexts.

Considering the air pressure automatic control specifications, we adopted a threshold value situated between 10 and 15 kPa for σ_P. On the first part of the tunnel, the alarm signal related to air bubble pressure P rang in 5 areas of less than 5 m long each (on a monitored length of nearly 200 m), among which the 2 recorded events (rings 159 and 204). On the opposite, this alarm signal rang only once on the second part (on a whole length of more than 400 m for which data were analysed), where confinement pressure dropped.

It appears therefore that such alarm signals are likely to be pertinent, for :

- they behaved differently according to the actual risk level (see the difference between the two parts of each tunnel);
- they rang for each of the two effectively verified events (and no one knows if the 3 other alarms did not actually correspond to a microcollapse which would have been filled by injection or which would not have been able to spread);
- they did not ring too often not to be taken into account.

In addition to these global checkings, several tests were made to check that the order of magnitude of these standard deviations were roughly independent of the arbitrary choice of 3 mn long time intervals, which was the case. Moreover, numerical tests were done to estimate the signal frequency above which these computed standard deviations became irrelevant, which gave us a basis for the future real-time systems specifications.

3.4 - Conclusion

These two a posteriori experiments make us confident regarding the possibility of real-time detecting of microcollapses.

Moreover, it appears that it will be easier and more efficient to work in real-time conditions, for:

- more parameters will be available for computation (pumps power and speed, mixing power...), which will allow redundancy, so that it will be possible to consider simultaneously several computed signals, and therefore to analyse special situations with the maximum of information;
- standard deviations will be computed during the whole duration of excavation (and the standards deviations computed for each 3 minute period long interval will be automatically averaged for the whole ring);

- it will also be possible to monitor parameters while the TBM is not boring (giving information about slurry losses for instance);
- the thresholds for each signal will be progressively estimated when the drivers will get a better experience of the soil and the TBM.

4 - RISK LEVEL VARIATION INDICATORS

4.1 - Basic concepts

Microcollapses can occur if the confinement is not adapted to the local geotechnical conditions around the TBM face: the slurry yield value may be too low for the soil permeability at the tunnel face ; or the slurry pressure may be too low for the soil strength behind and just above the tunnel face.

In the second case, which is the more frequent in typical sections, the soil strength is characterised by a cohesion c and a friction angle φ. Therefore, all methods able to detect variations in soil strength, in front or around the TBM, are potentially good indicators of variations in the microcollapse risk level.

Such methods must be based on concepts, or models, related to soil-TBM interaction.

For instance, an equivalent friction angle φ^* may be derived from the total thrust on the head (F_h) and the torque (C) thanks to relation : $\tan\varphi^* = 3\alpha C/DF_h$, where D is the tunnel diameter and α the ratio between effective soil-cutting head contact area and the total tunnel area. This last parameter is difficult to estimate, but this is not really important for one is especially concerned by variations in $\tan\varphi^*$.

Moreover, one can also study the variations of parameters which are likely to be correlated with soil strength. For instance, within a given geological formation, soil strength is generally well correlated with soil stiffness, characterised by the Young modulus E. Therefore, provided the geology is such that there is no reason for sudden variations in soil parameters, if one detects a progressive decrease of soil stiffness around the TBM, it is likely that soil strength is also decreasing.

This led us to the idea that the total friction F_f around the TBM could be an interesting indicator. Indeed, for given confinement conditions and overcut thickness, it is a function of the rate of soil convergence around the TBM, which is itself a function of soil Young modulus. As a matter of fact, it could be expected that a progressive increase of F_f (along several successive rings) would mean that soil modulus, and therefore soil strength, was progressively decreasing.

4.2 - Strasbourg experiment

Where the mortar quantities which actually had to be injected behind the lining were abnormally important, it appeared that the total friction F_f (computed as the difference between the thrust on the head and the thrust on the lining) exhibited a notable increase several rings before, and this before any alarm signal had rung and before problems were actually noticed by the pilots. These progressive increases were followed by sudden drops, corresponding to the point where microcollapses happened (which was generally confirmed by the pressure alarm signal).

It was more difficult to assess if the equivalent friction angle φ^* was adapted or not. However, it is clear that the average value of this parameter was notably higher in the first monitored part, where the soil conditions were actually better : by choosing an appropriate value for α, φ^* variations were less than 2° in each part, and its average values were respectively 35° in the "good" part and 25° in the "bad" part. However, this point will have to be confirmed on other tunnels because the two monitored parts were not adjacent, so that this variation of φ^* may also be due to variations in the cutter tools efficiency.

As for the alarm signals, these first ideas were directly tested on Clichy sewer.

4.3 - Clichy la Briche experiment

For practical reasons, we could only compute the friction F_f along the TBM. If we first consider the area before ring 159, where an important collapse was actually observed, it appears that F_f was constant (at 5%) between ring 146 and ring 153, and that it regularly increased up to doubling between the rings 153 and 159. It seems that the event which occurred at ring 159 (or at least the increase of risk level) could have been detected some 3 to 4 rings before it suddenly occurred.

This configuration of F_f curve (regular increase along 5 to 10 rings, followed by a sudden drop) was found for 5 of the 6 points where our alarm signals were activated. The only one for which the friction remained constant is ring 204, which is consistent with the fact that it was not due to a drop of soil strength, but to a sudden increase of permeability at the tunnel face.

4.4 - Conclusion

The tests run on the Clichy sewer confirmed the first conclusions obtained from the Strasbourg experiment concerning the use of total friction as an indicator of soil stiffness, and therefore of soil strength within a given soil layer. The measurement of this indicator is remarkably stable, for it is the resultant of local frictions averaged over a very important area (the TBM lateral area).

It is likely that the equivalent friction angle φ^* would constitute another interesting indicator.

In fact, several other indicators can be built with simple measured parameters, which could not be tested during our two experiments, for the necessary data had not been all stored. All these indicators, based on simple physical models or assumptions, could easily be computed and visualised during a real-time experiment, provided the hardware and software are designed for that purpose.

5 - PERSPECTIVES

The above mentioned developments and experiments show that it is possible, for tunnels bored with slurry pressure TBM in soft soils, to compute alarm signals, able to detect the occurrence of microcollapses at the tunnel face, and risk level indicators, giving the pilot elements to anticipate problems or risky areas.

Their computation in real-time conditions does not need exceptional storage or computation means, compared to traditional TBM data acquisition devices.

Alarm signals are easily interpreted by TBM drivers, for they are based on very intuitive notions, which are already used by skilled drivers (although they do not formulate them in terms of standard deviations) to determine whether everything is going right or wrong. Compared to the driver experiences, alarm signals offer several advantages:

- systematic and objective signal (independent of the driver skillness and of his present vigilance), redundancy of information (coupled with other alarm signals or indicators);
- possibility of detecting minor collapses (sensitivity of standard deviations computed regularly).

The interpretation of geotechnical variations indicators is less immediate, but this is not a problem considering the recent improvements in man-machine communication technologies, which provide clear messages about the interpretation or at least about the need for engineers or geotechnicians intervention.

A full real-time experiment on a whole tunnel is now the next step, in order to test several alarm signals and indicators altogether, to test the way pilots react to such systems (definition of alarm thresholds, of the way the results have to be visualised...) and to improve the system in close coordination with them). Such real-time full scale experiments will be run by Bouygues in 1996.

However, it seems obvious to us that all TBMs in soft soils and under urban areas will be equipped with Signal Aided Boring systems such as Bouygues' CATSBY system within several years. Such systems will not prevent from any collapse, for no automatic device is perfect, but they should contribute to reduce the risks in important proportions.

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