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Guidelines for comparing field or physical model observations with numerical simulations

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ABSTRACT: This paper presents short report on the activities of TC204 Working Group on "Guidelines to compare field or physical model observations with numerical simulations". The main objective of the WG is that of proposing recommendations concerning the comparison between calculated and observed behaviour, specifically adapted for the type of works covered by TC204, *i.e.* tunnels and open excavations in soft ground.

1 INTRODUCTION

At the TC28 Meeting held in Madrid in 2007, the decision was made to set up a Working Group (WG) devoted to the compilation of guidelines to compare field or physical model observations with numerical simulations. The general objective of the WG was to propose recommendations concerning the comparison between calculated and observed behaviour, specifically adapted for the type of works covered by TC204, *i.e.* tunnels and open excavations in soft ground.

It is clear that the activities of the WG will have to deal with the two rather different aspects of numerical prediction and field or model observation, and the best way to present them together so that their value can be enhanced. On the one end, there is the observed behaviour of a prototype structure or a physical model, on the other there are numerical simulations, necessarily obtained with some theory.

The real world provides performance, by which we mean the measured response of the structure under working conditions and in some—hopefully less common—cases, at failure. Prediction is an estimate of the expected behaviour of the structure under the working loads and in the conditions that are likely to occur during its life. Prediction is different from design, which must consider also extreme and unlikely events, and would not necessarily relate to measurable performance parameters.

The object of engineering computations is the behaviour of engineering structures (or physical models of structures) such as tunnels and excavations; the goals of engineering are successful design, construction and maintenance. On the other hand, theories typically deal with abstract entities, such as isotropic elastic bodies, or point loads. Starting from a small number of axioms and principles, for instance conservation laws or thermodynamics, theorems are obtained by demonstration and calculus. The goal, always achievable in the realm of theory, is that of obtaining exact, repeatable results.

The process that translates the real world into the theory is the so-called process of *modelling*, involving simplifications and assumptions. In order to be treated by theory, real objects such as engineering structures must become abstract entities. On the other hand, *predictions* obtained through analysis (the deflection of an elastic beam representing a retaining wall, the pore pressures generated around an expanding cylindrical cavity representing a tunnel, *etc.*) translate the results of theory to the real world.

2 MOTIVATION

The creation of the WG was partly motivated by the ever-increasing rate of publication of papers reporting some comparison between computed predictions and observed performance.

For instance, Figure 1 reports the number of published papers containing a comparison between predicted and observed behaviour of bored tunnels as a function of time. The situation is not significantly different if one considers published papers open excavations.

In the present Symposium, every session, with the exception of the present one devoted to the activities of TC204, contained some papers comparing the results of numerical calculations with some observations, see Figure 2.

The percentage number of such papers is obviously maximum in Session 5, devoted to design methods and predictive tools, where more than

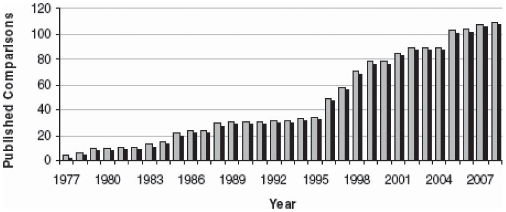

Figure 1. Number of published comparisons of predicted and observed behaviour for bored tunnels as a function of time (Negro *et al*, 2009).

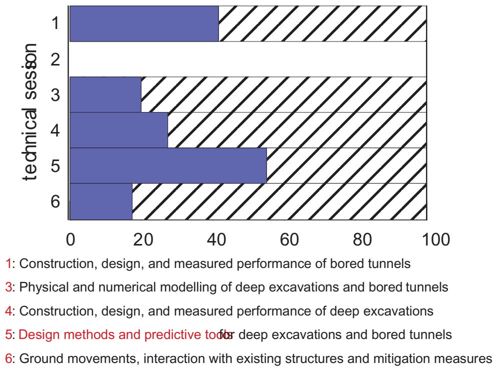

Figure 2. Percentage of papers containing comparison of predicted and measured behaviour of tunnels and open excavations in different sessions of TC28 IS-Roma 2011.

one half of the papers fall in the category, but it is interesting that even the mere illustration of a case history tends to be more and more often accompanied by some form of numerical calculation.

This is probably due to the rapid development of accessible numerical tools, such as Finite Element and Finite Difference codes, which makes it relatively easy to produce numerical computations, and yet, quite often, these comparisons are not very useful, or at least, not as useful as they could be, because they are not clearly or completely described.

Typical comments received by reviewers to papers submitted to this Symposium often included statements such as: "[…] more details are strongly needed about: drainage conditions, soil parameters, measured displacement, instruments and period of observation […]" or "[…] please provide information on the values of pore water pressure and, more generally, on the hydraulic conditions […]"; this is unfortunate as TC204 would like to set a virtuous example.

3 SCOPE

After the TC28 meetings of Shanghai (2008), Moscow (2010), and Alexandria (2010), the scope of the work of the WG, at least in a first stage, was narrowed down to deal primarily on reporting, rather than on providing recipes on how to design field instrumentation or carry out the predictions.

The guidelines will contain minimum requirements for meaningful reporting of comparisons of predicted and measured behaviour. Some of these are very general, such as a brief description of the general layout of the project and of the geological setting. These are typically included in most of the papers received to this conference, such as in the example given in Figure 3, extracted from Oteo *et al.* (2011), describing a new tunnel bored in alluvial soft soil under the Malaga Airport.

Information must also be contained on local soil conditions, including geometry of layers, groundwater conditions, and engineering properties of the ground, (unit weight, at rest horizontal stress, overconsolidation ratio, effective strength parameters, undrained shear strength, stiffness..). In other words some synthetic description of the geotechnical characterisation, leading to the definition of a geotechnical model of the site. It is obvious that not all the layers identified in the geological section need to be distinguished, as geotechnical layering may be simplified based on similar engineering properties.

Surprisingly, this was not often very well described in the papers to this Symposium, with comments received such as: "[…] add a figure with

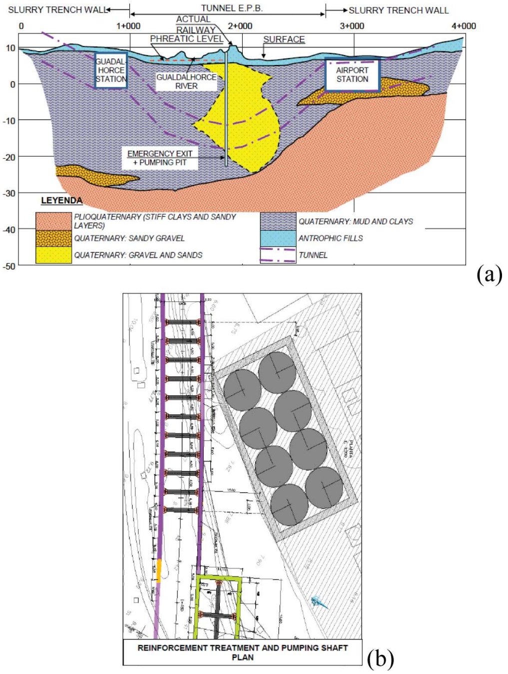

Figure 3. (a) Schematic geological profile of the area under examination, (b) detail of ground plan of the works.

the subsoil profile. The initial pore water pressure distribution has also to be defined […]" or "[…] please report in the paper the adopted mechanical parameters […]".

3.1 *Case history description*

Some details should be given on the case history at hand, such as construction and monitoring details. Of course this is going to be rather job specific and the guidelines by necessity will have to detail about different types of work, *e.g*. open excavation or tunnel. Despite the fact that no recipes are going to be provided in the guidelines, they may serve as a sort of checklist leading to better design of monitoring for more comprehensive comparisons of field and experimental data with the results of numerical modelling.

Some consideration will have to be given to the main factors affecting the behaviour of the structures. For instance, for open excavations, these will include the geometry of the excavation, not just its depth but also its plan area, as this may determine a particular behaviour, all other factors being the same. For instance, construction of a new conference centre required a very wide excavation (240 m × 35 m, for a total plan area of 32400 m^2) for a depth of about 15 m b.g.l., see Figure 4.

The purple area in the map corresponds to a tower founded on a piled raft, with 1 m diameter and 25 m long piles, the green area to the foundations of an auditorium resting on strip footings and localised pads, again with 1 m diameter and 30 m long piles. The rest of the foundation is a raft with a thickness of about 1 m. Because of the significant unloading of the underlying clay layers, if the joints between the raft and the piled foundations are sealed too early very large swelling pressures are expected. This is a case where an observational approach may be adopted in which the consolidation phenomena and the excess pore water pressures in the clay layer are monitored to optimise the construction process. For tunnels, geometrical details will include depth of the tunnel axis or cover and diameter of the tunnel.

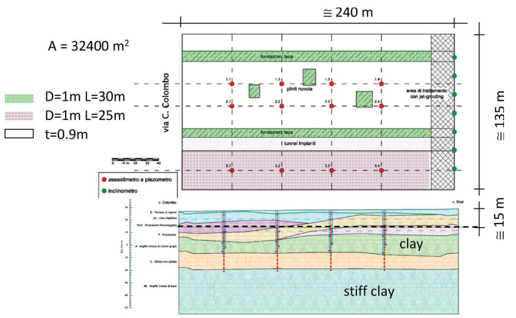

Figure 4. (top) Plan and (bottom) section of large excavation.

Factors relating to construction will also have to be reported, for instance, again for open excavations, the procedures for the installation of the retaining structure, *e.g*.: slurry trenching and concreting of diaphragm walls, but also the maximum depth of excavation before any support is provided, the sequence of construction stages, details of the support structures such as struts, whalers, anchors, pre-stressing, etc., likely pore water pressure reductions due to water ingress in the excavation or dewatering, any ground treatment, etc.

If structures exist near the excavation there will be external loads to be detailed and the position of the structures relative to the excavation will have to be considered.

3.2 *Layout of instrumentation*

The guidelines will contain examples of typical layout of instrumentation for specific geotechnical purposes, similar to those reported in Figure 5 and Figure 6.

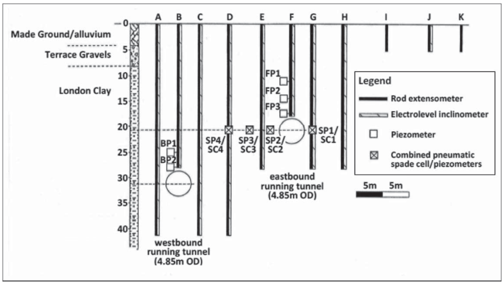

Figure 5. Layout of instrumentation at St. James's Park. (after Nyren, 1998).

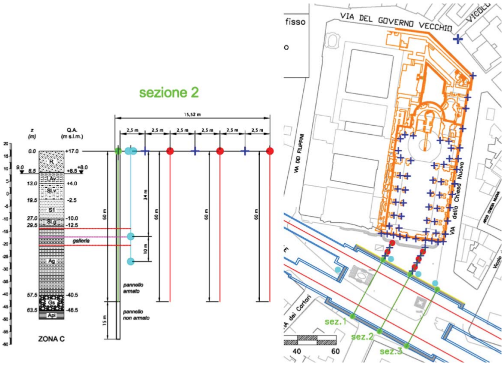

Figure 6. Proposed layout of instrumentation at Chiesa Nuova Station (courtesy of Metro C spa).

Figure 5 is the green field control section installed at St. James Park to monitor the effects of excavation of the of the running tunnels of the Jubilee Line Extension (Nyren, 1998), including surface levelling points, inclinometers, extensimeters and piezometers.

Figure 6 is the proposed layout of instrumentation around the deep open excavation for Chiesa Nuova Stations of contract T2 of Line C of Roma Underground, presently at the design stage.

In this case instrumentation includes reference points for precision levelling, both of the ground surface and of the nearby church, inclinometers and extensimeters for subsurface displacements, piezometers in the fine grained layers. In the same sections where bending moments are measured on the retaining structures by means of strain gauges, inclinometers are cast in the panels to measure horizontal deflections of the wall, to verify design assumptions and control construction.

Special monitoring schemes may be devised for particular purposes, such as, for instance, control sections to measure ground movements and stress redistribution due to slurry trenching and concreting.

4 CLASSIFICATION OF PREDICTION

A number of papers apply the term "prediction" when describing the results of numerical or analytical calculations, without clarification of when the prediction was carried out. Following a recommendation by Boone (2005), in the guidelines it will be strongly recommended that, if the term "prediction" is to be used in future publications, it must be explicitly described in terms of a "prediction class" as introduced by Lambe (1973) nearly 40 years ago, who classified the type of predictions according to whether they are made before (class A) during (class B) or after (class C) construction, and according to whether or not the results were known or not known to the authors of the prediction (see Table 1).

Most of so-called predictions are in fact class C1, so they should be better described as back analyses of the observed behaviour.

Another important classification which was introduced by Negro (1998) with specific reference to tunnel works regards the thoroughness of the prediction (see Table 2). Four categories of increasing thoroughness are defined depending on what was the object of the prediction. Ideally, a prediction should include comparisons of the complete ground displacement field and lining loads. In practice, the easiest predicted feature is a surface settlement trough, but very rarely is the field of subsurface or horizontal displacements predicted or compared with field observations.

Table 1. Classification of prediction (Lambe, 1973).

Class	Time of prediction	Results
A	before	–
B	during	not known
B1	during	known
C	after	not known
C1	after	known

Table 2. Thoroughness of tunnel predictions (Negro, 1998).

Category	Vertical displ.		Horizontal displ.		Lining loads
1	X	or	X	or	X
2	X	and	X	–	–
3	X	or	X	and	X
4	X	and	X	and	X

This can be easily adapted to the case of supported excavations, by looking not only to the horizontal deflections of the wall, which are generally easily matched by numerical calculations, but also to vertical displacements of the ground behind the retaining structure or subsurface vertical displacements, bending moments in the wall or strut forces and anchor loads.

5 NUMERICAL SIMULATION

The minimum requirements for reporting should also include details on the prediction, which will include a model of the problem, some constitutive assumptions for the soil and a procedure of analysis.

The geometry of the adopted mesh, the boundary and initial conditions and their changes due to excavation and loading should be specified.

Clear statements will also be needed on the adopted constitutive model for the soil, the parameters required by the model and if and how they are determined from the available data. In some cases, some if not all the parameters, might be obtained by back analyses of some of the available data and used to predict the rest of the data, using an inverse analysis procedure that uses construction monitoring data to update predictions of deformations for supported excavation systems (Finno & Calvello, 2005).

This all seems quite obvious and yet, in the comments of the reviewers we find requests such as: "[…] an example of mesh used (or its dimension) should be included […]", "[…] boundary conditions at wall position must be better specified […]", "[…] finite element analyses are mentioned in the paper, but no details of the analyses are provided: code? constitutive equation? […]",

"[…] the complete set of soil model parameters (unit weights, strength (cohesion, friction and dilation) should be presented […]".

Finally, the procedures of analysis have to be specified. Here we are not thinking of fine numerical issues such as integration schemes, but rather basic information on the ways the analyses were carried out: three- or two-dimensional (plane strain, axi-symmetric), by finite element or finite difference method, drained or undrained, coupled or uncoupled, with or without interfaces at soil structure contacts, etc.

Again from the comments of reviewers: "[…] a series of numerical analyses (perhaps 3D? it is unclear) […]", "[…] no information on whether these are effective stress or total stress […]", "[…] explain whether numerical analyses are carried out in terms of total or effective stress, and hydraulic boundary conditions for the saturated case […]".

6 PERSPECTIVE AND CONCLUSIONS

The activities that the working group has been busy with are a systematic review of case histories to identify areas of weakness in reporting. The questions we would like to answer to are: what is it that is missing in most cases? And how can this be improved? This will be mostly carried out with reference to case histories of deep open excavations, as there is already quite a lot of work that has been carried out on tunnel case histories.

An attempt to identify the scope of measurements (*i.e.*: verification of basis for design, document effects on surrounding structures, basic research, *etc*.) and relevance of particular instrumentation for scope is currently under way. Also an effort is being made to rationalise recommendations for standard ways to reduce and, represent data.

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