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A DATABASE FOR CASE HISTORIES AND NUMERICAL MODELLING

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ABSTRACT

This paper deals with a bibliographic database dedicated to the comparison between numerical results and *in situ* measurements for geotechnical structures. This database, called MOMIS, has been developed by LCPC and ECN for several years. To date, it comprises a total of 416 case histories. The generation of MOMIS has relied on a technologic watch in the field of numerical modelling. The database can be used to highlight modelling principles (in order to provide a guide for good modelling practice to users) and deviations between results given by numerical models and values measured on actual geotechnical structures. It also reflects the evolution of the accuracy of numerical computations.

INTRODUCTION

Numerical methods are now well established as an analysis tool in many engineering problems, and practical applications have been growing at prodigious rate in recent years. With the increase in modelling applications and computing codes, it becomes essential for users that the code be well validated for different point of view and the range of possible applications assessed in a reliable manner.

In the field of geotechnical engineering, validation of numerical codes is of uppermost importance for three reasons:

- results are used for the design (displacements of soil, forces and moments in structures, etc.);
- complex constitutive laws are involved for modelling the behaviour of soils and rocks ;
- complex computations are carried out by users.

The validation of a numerical model is achieved in terms of agreement between numerical results and experimental data. Accordingly, a literature survey is indispensable. Over the past thirty years, only two qualitative compilations, by Duncan (1994) and Gens (1995), and a study devoted to underground facilities (Negro et de Queiroz, 2000) have been produced. No actual quantitative "assessment" has ever been drawn of the deviations observed between numerical modeling efforts and measurement campaigns. In light of this lack of references necessary for evaluating the capacity of both soil constitutive laws and software to reproduce complex situations, the Laboratoire Central des Ponts et Chaussées (LCPC) and the Ecole Centrale de Nantes (ECN) have

instituted a technology watch program to inventory these comparisons and estimate the resultant "model error" (Mestat, 2001a).

This technology watch has covered more than four hundred case histories where comparisons between numerical predictions and field measurements have been reported (horizontal and vertical displacements, excess pore pressures, stresses, etc.). Only *in situ* measurements were considered. The physical models (laboratory tests 1g or centrifuged models) were not taken into account in this survey. As a means of collecting and processing these data, the MOMIS database has been developed.

MOMIS DATABASE

The bibliographic database, called MOMIS (acronym for "Modélisation des Ouvrages et Mesures In Situ"), comprises case histories originating from articles, conference papers, reports and doctoral theses identified as part of the technology watch program. The data set extends back to 1972, with entries being evenly distributed over time (figure 1).

The database currently contains 416 case histories corresponding to the modelling of embankments (84), tunnels (135), sheet-piled retaining structures (66), diaphragm walls (102) and embankments on improved soils (29). Figure 2 reveals that almost half of the cases studied originated in Europe, followed by Asia, North America, Africa and South America.

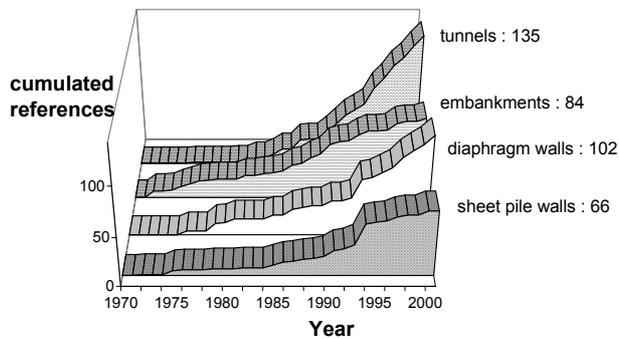


Fig. 1. Cumulated number of references over thirty years

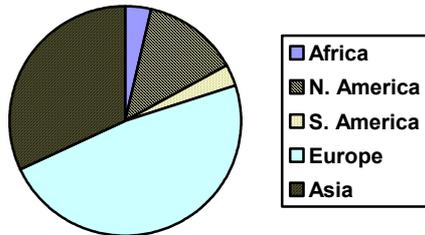


Fig. 2. Experiment locations

Following the classification by Lambe (1973), the vast majority of modeling efforts recorded (382 case studies) pertain to class C predictions (ie a posteriori predictions) and only 34 cases concern class A predictions (before construction without knowledge of measures). Class A predictions are the ideal type of prediction to evaluate the performance of numerical modelling. Unfortunately they tend to be rather rare. Their limited number is due to the cost of experiments and more predominantly to their time requirements, which seem to be incompatible with the constraints imposed by construction economics.

Even though class C predictions are less demonstrative, it is valuable and useful to draw lessons from these comparisons from both an engineering and research standpoint as well as to derive recommendations for subsequent modelling set-ups (choice of model and guidelines for controlling results) and to quantify the model error.

For each type of geotechnical structure, the number of case histories would seem high enough to be able to produce a statistical overview covering a thirty-year period of numerical computation-measurement comparisons. The complete list of references, relative to embankments and tunnels, have been published (Mestat, 2001b, 2002).

An electronic version using the ACCESS database management application is being implemented in coordination with the Civil Engineering Laboratory of the Ecole Centrale de Nantes (Mestat and Riou, 2002). This database is mainly devoted to Class A predictions. For now, the information relative to 13 blind prediction competitions is stored in 63 tables linked together in order to facilitate the data analysis.

For each case study eight families serve to organize and collate the following informations:

- type of analysis (drained vs. undrained condition, consolidation, dynamic, cyclical);
- composition of the ground;
- construction technique employed, actual dimensions of the structure;
- constitutive laws for natural soils and construction materials, parameters;
- computational model (dimensions, type of finite elements, mesh density, boundary conditions, loadings, time step, construction project phasing, interface laws, etc.);
- set of numerical data for the comparison between computation results and measured values;
- conclusions drawn from the comparison (maximum deviation, relative errors, etc.);
- bibliographical references.

For the same experimental case, several numerical studies may be generated; such is the case for example when holding a blind prediction competition or a comparison between several constitutive laws for soils.

REVIEW OF CASE HISTORIES IN MOMIS DATABASE

The numerical studies were mainly two-dimensional finite element analyses (Table 1). Some more recent 3D analyses are included in the database (9% of the references). The quantitative comparisons between predicted results and field measurements depend on the geotechnical works.

Table 1. Number of comparisons with 2D FE analysis

Embankment (end of construction)	
- maximum settlement on center line	39
- maximum lateral displacement in depth (toe of slope)	24
- maximum excess pore pressure on center line	16
Embankment (long term)	
- maximum settlement on center line	38
- maximum lateral displacement in depth (toe of slope)	26
Tunnels (end of construction)	
- maximum surface settlement (transversal model)	120
- point of inflexion of settlement trough	87
- crown settlement	30
- maximum horizontal displacement	32
Sheet-pile walls (end of construction)	
- maximum horizontal displacement of the wall	69
- maximum settlement behind the wall	37
- maximum bending moment in the wall	24
Diaphragm walls (end of construction)	
- maximum horizontal displacement of the wall	77
- maximum settlement behind the wall	19
- maximum bending moment in the wall	18

The data contained within MOMIS database can serve to analyse, in statistical terms, the characteristics of meshes and to highlight modelling principles.

Geometrical Finite Element Model

Given that embankments, retaining structures and tunnels quite often exhibit a much greater length than width, their performance is often studied using a transversal section in plane strain. From the MOMIS data, we can justify the minimum recommendations for meshes used in both vertical and horizontal directions (Table 2). These recommendations are valuable for the numerical models which need not incorporate the presence of substratum near the surface, obstacles or other neighbouring interactions. For the mesh density, there is no real information in the references stored in the database because authors tend to offer little comment on the choices inherent in carrying out geometrical discretization.

Table 2. Minimum dimensions for 2D plane strain meshes

Structures	Total length	Total height
Embankments	3 L	4 h
Retaining structures	4 D	2 D
Tunnels	5 d	2,5 H

L=1/2 width of embankment base; h=embankment height; D=height of the wall; d=tunnel diameter; H=tunnel axis depth.

The majority of 3D models are made for tunneling problems: intersection of galleries, influence of tunnel face, construction sequences which is really 3D, etc. At present time, it is difficult to deal with 3D modeling because there are not many case histories. What we can observe is the following point : in 3D mesh, the section perpendicular to the tunnel axis has generally extensions similar to those fixed for a 2D modeling. For example, the ratio total height of mesh / tunnel axis depth is about 2 for 3D meshes reported in MOMIS database. Of course the 3D mesh density is less refined than for 2D mesh and often not sufficient. A future survey will be made with complementary publications even if there are no comparisons with measurements. It is essential to provide good recommendations for 3D numerical models.

Type of Analysis for Geotechnical Structures

Three theoretical approaches are considered : undrained conditions (29%); drained conditions (46%) and consolidation (25%). From a historical perspective, the first two analyses preceded the third. Consolidation computations with non-linear behaviour were not possible before the existence of high-speed computers. Nevertheless, a comparison between modeling of embankments, tunnels and retaining structures shows a great difference in the types of analysis (percentages are listed in Table 3). The consolidation approach is rarer for tunnels and retaining structures.

Table 3. Type of analysis (%)

Structures	Drained	Undrained	Consolidation
Embankments	13	20	67
Diaphragm walls	34	50	16
Sheet-piles	48	42	10
Tunnels	73	14	13

Constitutive Laws for Soils

The percentages of constitutive laws used for natural soils in the cases histories are listed in Table 4. The complexity of excavation sequences and computation time lead often to using simple constitutive laws for soil in the problems of tunnels and retaining structures: in more than 60% of case histories the constitutive law is elasticity (EL) or perfect plasticity (EP). On the other hand, the simple and monotonic loading in embankment problems allows to consider elastoplasticity with strain hardening or elasto-visco-plasticity for soft soils. Nevertheless the general trend has favored use of strain hardening models.

Table 4. Type of constitutive laws used for soils (%)

Structures	EL	EP	EPH	EVP	HP
Embankments	11	12,5	49	27,5	0
Diaphragm walls	40	28	25	4	3
Sheet-piles	27,5	51	21,5	0	0
Tunnels	23,5	36,5	34	8	0

EL=linear or non linear elasticity; EP=elastoplasticity without hardening; EPH=elastoplasticity with hardening; EVP=elasto-visco-plasticity; HP=hypoplasticity.

2D COMPUTATION MEASUREMENT COMPARISONS

For 2D FEM modelling, comparisons between measured and computed values were made at the end of construction and at long term (particularly for embankments on soft soils). For example, the analysis of surface settlement in tunnel modelling can be achieved with figure 3 (settlement) and figure 4 (characteristics of trough).

Most class C predictions have led to relatively satisfactory results for the maximum vertical settlement on the surface at the end of construction (Figure 3). The points corresponding to computation values and measured values are primarily located within the boundaries defined by the results from class A predictions. This observation was expected because class C predictions can be improved by the knowledge of the measurements.

The quality of predictions focused on the settlement trough is also acceptable (distance of the point of inflexion, figure 4), but its width is generally overestimated.

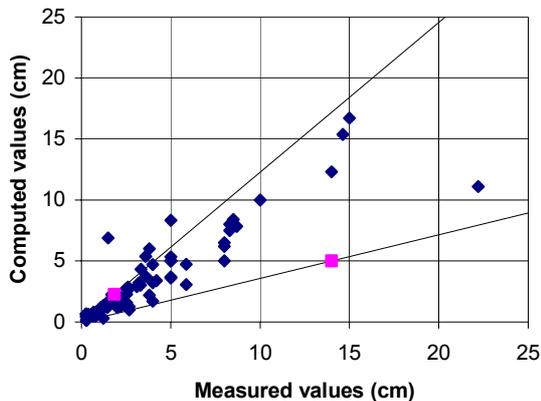


Fig. 3. Comparison in the maximum settlement on the tunnel axis at the end of construction (squares represent class A predictions)

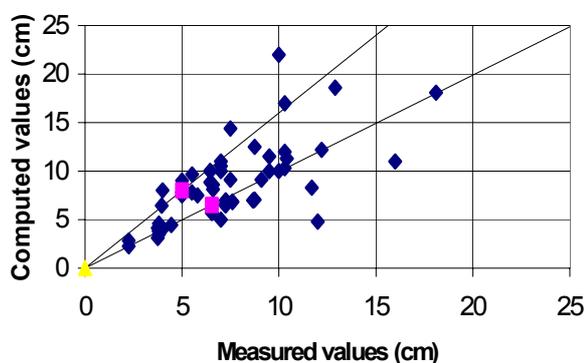


Fig. 4. Comparison in the transverse distance of the point of inflexion of settlement trough

The measured values of maximum lateral displacements in depth are rarer. Figure 5 shows the comparisons between computed results and measurements provided by inclinometers near the tunnel axis.

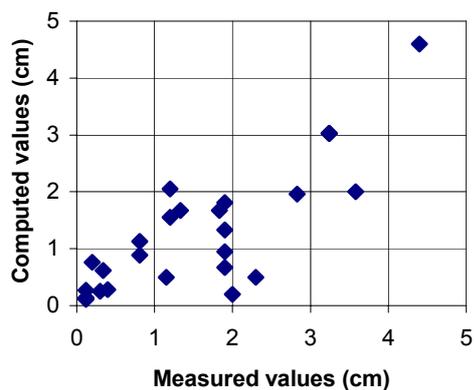


Fig. 5. Comparison in maximum lateral displacements in depth at the end of construction

Same diagrams can be drawn for embankments or retaining structures (Mestat and Riou, 2002; Mestat and Bourgeois, 2002). This analysis has enabled quantifying the model error committed during the modeling. During this year, a new synthesis has been made for all the references in the MOMIS database and new estimations of relative model errors provided on main measured variables.

ESTIMATION OF RELATIVE MODELLING ERRORS

The modelling error is estimated after numerical computations, indeed it is the “sum” of the errors related to the software, its use, the hypotheses of modelling, the approach employed to obtain the mechanical and hydraulic parameters. In deriving this error, class A predictions are obviously the best fitted. Unfortunately they are rarer. Then all the references included in MOMIS database were taken into consideration.

For each geotechnical structure and each measured variable, five intervals are distinguished for the relative error e : $[0, 25\%]$, $[25, 50\%]$, $[50, 75\%]$, $[75, 100\%]$ and $[100\%, +\infty[$. The relative error is the absolute value of the difference between the computed value and the measured value, divided by the measured value.

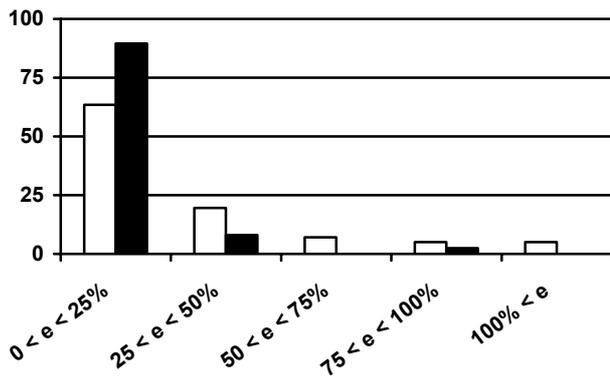
Figures 6 show the distribution of relative error for the maximum surface settlement (figure 6a) and the maximum lateral displacement at the toe (figure 6b). On the same figures, the results at the end of construction and at long term are represented. The quality of predictions is satisfactory for settlements specially at long term. In contrast the modeling of lateral soil movements is often unsatisfactory ; at short term only 58 % of the predictions reveal a relative error below 50 %, and 21% have a relative error of above 100%.

For retaining structures, best results are obtained with horizontal displacements of the wall (figure 7). On the other hand, vertical displacements on soil surface behind the wall (figure 7) and heave of the bottom excavation present important relative errors : 25% of case histories reveal a relative error of above 100%.

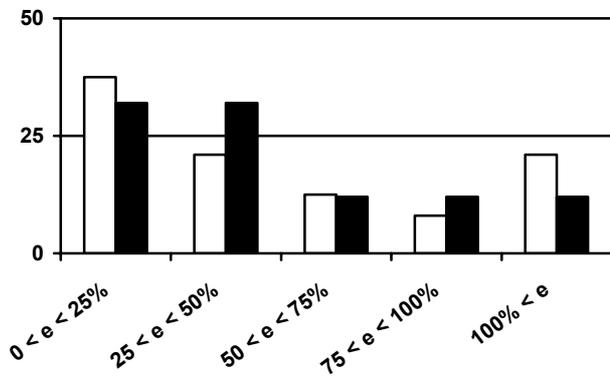
For tunnels, the modelling of the surface settlement is generally satisfactory (figure 8) and the distance to the point inflexion of settlement trough is well described. Even the width of trough is often overestimated by FE results, it is possible to simulate in satisfactory way the settlement trough when the mechanical parameters can be estimated with a sufficient precision.

Figures 6 and 9 show that FE models lead at present time to a poor simulation of lateral soil movements in the case of embankments and tunnels. In contrast figure 7 shows that horizontal movements of retaining structures are relatively well described and not the vertical soil movements. This difference confirms that the main movement of each geotechnical works is relatively well simulated by the

constitutive laws used in numerical models. Unfortunately it is not sufficient because a “good numerical model” must simulate simultaneously all the aspects of soil-structure behaviour.



(a) Maximum surface settlement on the embankment axis



(b) Maximum lateral displacement in depth (at the toe)

Fig. 6. Modelling errors for embankments – Comparison between results obtained at the end of construction (in white) and at long term (in black)

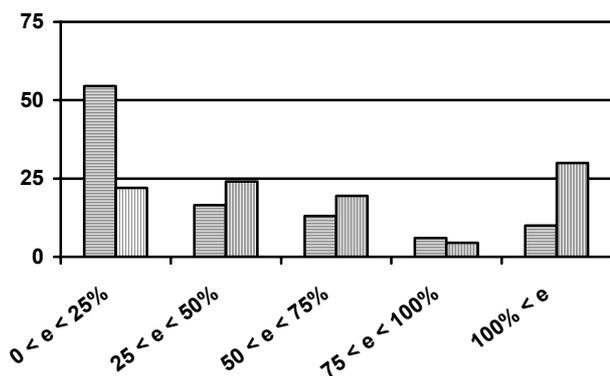


Fig. 7. Modelling errors for retaining structures – Comparisons between maximum horizontal displacement of the wall (horizontal lines) and maximum vertical displacement of soil surface behind the wall (vertical lines)

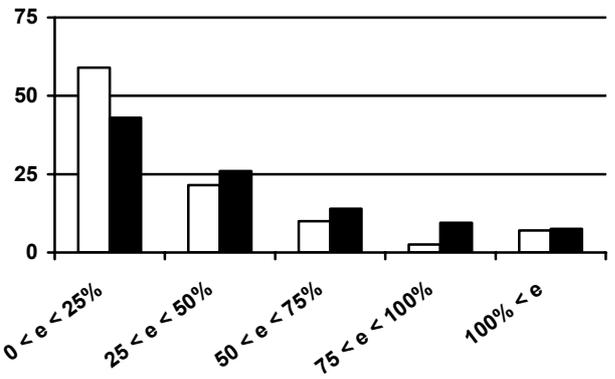


Fig. 8. Modelling errors for tunnels at the end of construction – Comparison between maximum settlement on the axis tunnel (in white) and the distance of the point of inflexion of the settlement trough (in black)

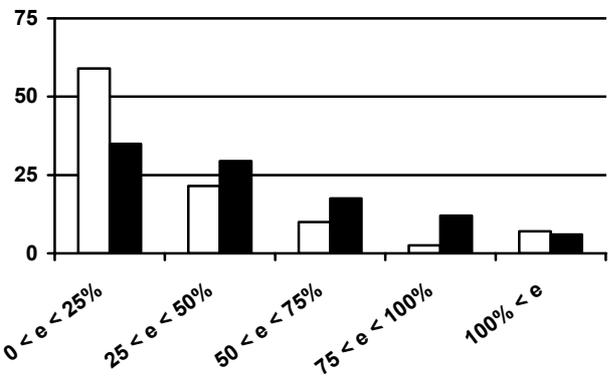


Fig. 9. Modelling errors for tunnels at the end of construction – Comparison between maximum surface settlement (in white) and maximum horizontal displacement tunnel in depth (in black)

ELECTRONIC DATABASE FOR CLASS A PREDICTIONS

As regards the validation and demonstration of a model's capacity to predict structural behaviour, class A predictions (benchmarks) are the most incisive, yet remain the least frequent. In order to collect all the information about each benchmark and to provide better data access, an electronic database is developed (Mestat and Riou, 2002). At the present time its structure exclusively involves the class A predictions and the academic benchmarks (comparison of numerical calculations without measurement). The aim of this tool is to directly link the in-situ measurements with the predicted values (or predicted values with each other), the type and the parameters of the modelling. By this way, some useful indications regarding the current practice in modelling (discretization, boundary conditions, type of analysis, constitutive relationships, rheological parameters, etc.), their bias, the problems that the authors and participants encountered in these benchmarks, are expected.

For now (august 2003), 13 benchmarks, 66 soil layers characterised by benchmark authors, 184 numerical modelling reports, 369 soil layers characterised by benchmark participants, 13 constitutive models, 6400 numerical results (settlements, horizontal displacements, water pore pressure, forces, moments) have been stored in the database (Table 5).

In the database, benchmarks are distinguished by the reference data :

- industrials benchmarks with *in situ* measurements;
- semi industrial benchmark with laboratory measurements;
- academic benchmarks without reference (measurement) to a work. The aim of these benchmarks is to compare codes and settings up of modelling.

Table 5. Blind prediction competitions stored in the electronic database (references are listed in Riou et al. (2003))

Geotechnical work	Organisation	Place	Nbr. of Partic.
Embankment	FNRA	Finland	5
Embankment	DBR	Gloucester Canada	5
Embankment	Instit. of Engineers Road Administration	Muar Flats Malaysia	4
Retaining wall Anchored wall	Univ. of Technology	Graz Austria	15
Retaining wall Strutted wall	Univ. of Technology	Graz Austria	12
Retaining wall Strutted wall	Univ. of Karlsruhe	Hochstetten Germany	43
Spread footing	Univ. of Technology	Graz Austria	6
Spread footing	Texas A&M Univ. FHWA.	USA	31
Spread footing	Texas A&M Univ. FHWA.	USA	31
Spread footing	Texas A&M Univ. FHWA	USA	31
Spread footing	Texas A&M Univ. FHWA	USA	31
Spread footing	Texas A&M Univ. FHWA	USA	31
Tunnel	Univ. of Technology	Graz Austria	12

A first analysis of data contained in the database has been performed to know the use of constitutive models, the distribution of the values of some mechanical parameters, and the distribution of modelling error.

The analysis of constitutive models used in blind prediction competitions show the preponderance of Mohr-Coulomb models (54 %) and its distribution on the whole of geotechnical works seems in accordance with the idea of common practices in modelling, especially for projects (figure 10).

It is worth noting that elastoplastic models with no hardening are more currently used in class A predictions than in class C predictions. This fact is due to many reasons :

- for the purpose of comparisons, some benchmarks required the use of only one model. Mohr-Coulomb model is generally imposed as the more common model;
- benchmark participants prefer a simple and robust model (like for a project);
- some laboratory or *in situ* tests required for complex constitutive model are not available in the geotechnical report of the benchmark;
- class C predictions are often performed to test new sophisticated models.

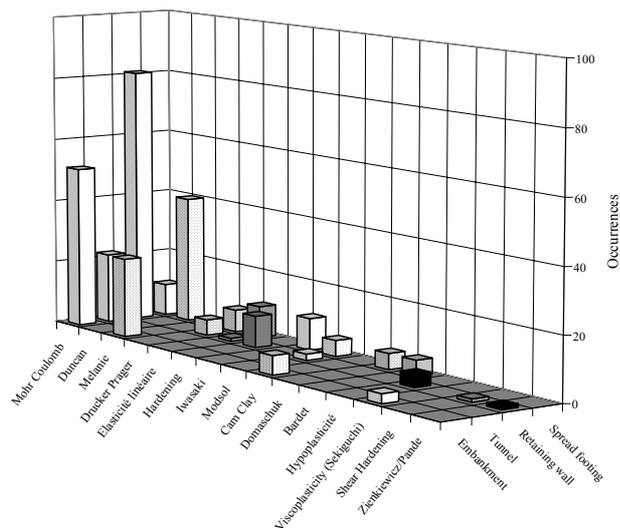


Fig. 10. Constitutive relationships and geotechnical works modelling – Electronic database for class A predictions

The second study indicates the spread of Young’s modulus values in the Mohr-Coulomb model independently of the geotechnical work (see figure 11). The Young’s modulus used in these class A predictions is an “interpreted” value of soil stiffness. This value takes into account the rate of deformation in the geotechnical work. So, this figure exhibits a large scatter not representative of intrinsic elastic modulus. This distribution should be compared to the equivalent class C distribution in order to know the possible bias between “interpreted” value (class A prediction) and possible “adapted value” (class C prediction).

A similar analysis has been performed on friction angle of sand provided by participant using the Mohr-Coulomb model (see figure 12). In spite of its “more intrinsic” character, the scatter is very large: from 31 to 42 degrees. The distribution is uniform excepted for 35 and 40 degrees. No explanation is put forth, beyond the fact that 35 and 40 are multiple of five !!!

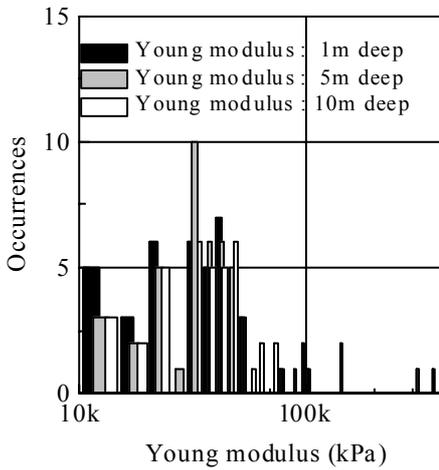


Fig. 11. Young's modulus distribution, Mohr Coulomb model (electronic database, class A predictions)

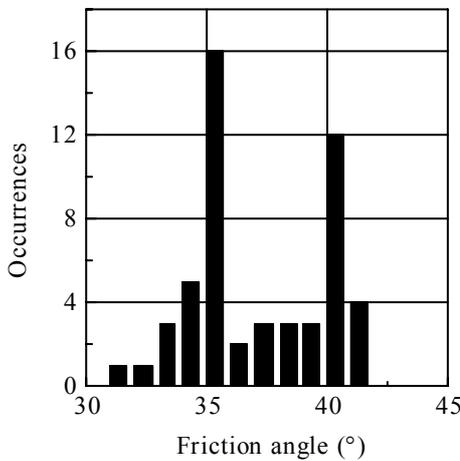


Fig. 12. Friction angle distribution, Mohr Coulomb model, (electronic database, class A predictions)

At least, an example of numerical modelling error distribution is provided in figures 13 and 14. The error expression takes the following form :

$$Err = \frac{(\text{measure} - \text{calculation})}{\text{measure}}$$

These distributions concern two blind prediction competitions in relation with embankment: Haarajoki and Muar flats embankment. It is worth noting that the two benchmarks presents similar general distributions:

- if the tail of distribution in conservative area (negative values of error) is neglected, calculation results in a maximum over-estimation ratio of 4;
- the greatest occurrence of settlement error is located between 0 and 0.5. So, the calculation is slightly unconservative;

- this greatest occurrence in the case of lateral displacement is located in conservative area. However, this displacement can be overestimated or over estimated. This error on lateral displacement is four times greater than the one on settlement

The Haarajoki competition presents a larger global modelling error. This is mainly due to the fact that the calculation concerns two areas, one of which is composed of drains, making the modelling more complicated.

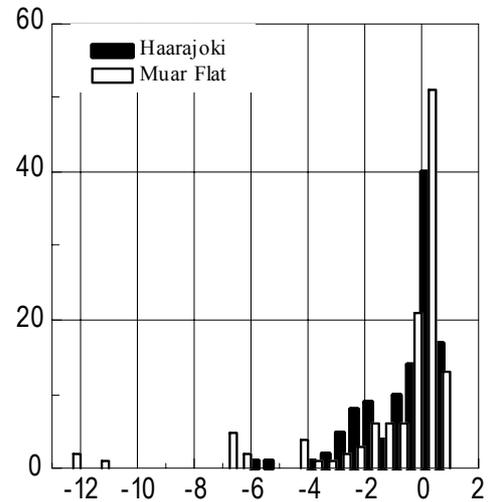


Fig. 13. Distribution of modelling error. Settlement under the embankment

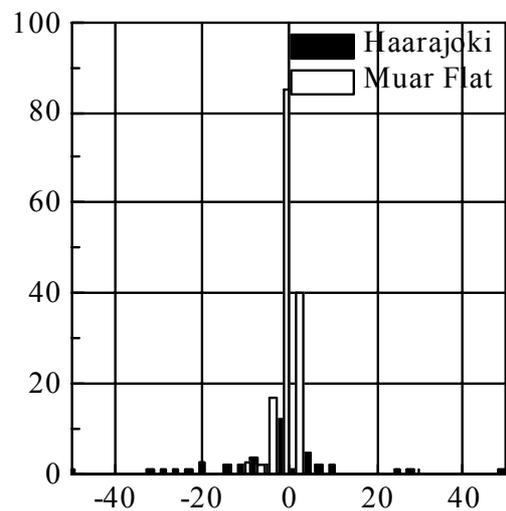


Fig. 14. Distribution of modelling error. Lateral displacement under the embankment

As for class C prediction analysis, the long term displacements are better estimated, but the error order is not the same. So, if class C predictions are needed for the validation and calibration of models, class A prediction are essential for the evaluation of modelling error in project conditions.

CONCLUSIONS

The “Laboratoire Central des Ponts et Chaussées” and the “Ecole Centrale de Nantes” have been conducting a technology watch mission over the past several years with respect to comparing finite element model results with in situ measurements. The primary objective is: to preserve the record of these models and their comparisons with *in situ* measurements, to draw lessons in the practice of geotechnical modeling, to provide orders of magnitude for computation results, and to quantify the modelling error. The information extracted from the bibliographical analysis has been combined into a database called MOMIS.

The MOMIS database is just in the nascent stages of its development. Collation of the references has served to identify a few general conclusions, such as:

- the modelling error is less than 50% for the settlement predictions at the end of tunnel or embankment construction and for the horizontal displacement of a retaining structure at the end of construction;
- the modelling error remains high for the lateral displacements in tunneling and for the vertical settlement behind a retaining structure, with a significant number of relative errors surpassing 100%.

On the other hand, an electronic database is currently being developed at EC Nantes (with the ACCESS database management software) specially for the blind prediction competitions (class A predictions). The aim of this specific database is to link the in-situ measurements with the predicted values, or with the parameters of the modelling. By this way, some useful indications regarding the current practice in modelling, their bias, the problems that the authors and participants encountered in these benchmarks, are expected.

Finally it is essential to continue conducting these computation-measurement comparisons along with additional full-scale experiments. We need to ascertain the degree of realism in the models and to define modelling methodologies specific to each type of geotechnical structure.

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