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Prediction and performance : numerical modeling of sheet pile walls and diaphragm walls

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ABSTRACT: A database dedicated to the numerical modeling of geotechnical structures as well as to the comparison between FEM results and *in situ* measurements has been developed at LCPC. This database, called MOMIS, currently comprises a total of 369 case studies, 135 with underground works, 66 with sheet-piled retaining structures and 84 with diaphragm walls. The generation of MOMIS has relied on a technology watch effort implemented in the field of finite element modeling. Use of this database has served both to highlight modeling principles and to quantify deviations between results given by numerical models and values measured on actual geotechnical structures.

1 INTRODUCTION

Over the past thirty years, publications have regularly reported on comparisons conducted between finite element results and measurements taken on geotechnical structures. Nevertheless no actual quantitative assessment has ever been drawn of the deviations observed between finite element modeling efforts and measurement campaigns. In light of this lack of references necessary for evaluating the capacity of both constitutive laws and software to reproduce complex situations, the Geotechnical Structures Computations Unit of Laboratoire Central des Ponts et Chaussées (LCPC) has been conducting a "technology watch" mission with respect to comparing finite element model results with measurements on actual geotechnical structures. The primary objective is to preserve the record of these models and their comparisons (Mestat, 2001a). Even though numerical models are imperfect when incorporating the complexity of geotechnical realities, it is still valuable and useful to draw lessons from these comparisons from both an engineering and research standpoint as well as to derive recommendations for subsequent structural modeling set-ups (choice of model and guidelines for controlling results) and to quantify the model error.

As a means of collecting and processing these data, the MOMIS database has been developed. MOMIS is dedicated to the numerical modelling of geotechnical structures as well as to the comparison between computational results by finite element method (FEM) and in situ measurements.

2 MOMIS DATABASE

The informations extracted from bibliographical analysis have been combined into the MOMIS database (acronym for « Modélisation des Ouvrages et Mesures In Situ »). It comprises case studies originating from research studies conducted by the LPC network of laboratories, articles, conference papers 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 since. The most intense periods of publication correspond with the organization of international conferences and symposia on Soil Mechanics (ISSMGE[1]) or on applied computational methods in the field of geotechnics (IACMAG[2], NUMOG[3], NUMGE[4]) (see Figure 1). Nearly 75% of the references appear in conference proceedings, 20% stem from articles and the remaining 5% or thereabouts from reports or theses. Some documents were rejected due to insufficient detail on the model, the case under evaluation or the conclusions derived. The vast majority of modeling efforts recorded pertain to class C predictions (ie a posteriori prediction, following the classification by Lambe, 1973).

In 2001, the references for sheet pile and diaphragm walls have been added in the database MOMIS. It currently contains 369 case studies corresponding to the modeling of embankments (84), tunnels (135), sheet-piled retaining structures (66) and diaphragm walls (84) (both class A and C predictions). These numbers seem high enough to make it possible to produce a statistical overview covering a thirty-year period of finite element modeling (2D or 3D) and computation-measurement comparisons (Table 1; only for 2D FEM results).

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;
- computational model (dimensions, type of finite elements, mesh density, boundary conditions, loadings, time step, construction project phasing, interface laws, etc.);
- set of curves for translating the comparison between computation results and measured values;
- conclusions drawn from the comparison (maximum deviation, relative errors, etc.);
- bibliographical references contained in the documents submitted to analysis.

For the same experimental case, several numerical studies may thereby be generated; such is the case for example when holding a blind prediction competition.

A computerized version using the ACCESS database management application is being implemented in coordination with the Civil Engineering Laboratory of the Ecole Centrale de Nantes. In awaiting the release of this computerized version, manual database operations with tables have enabled drawing some valuable lessons from nearly thirty years of modeling efforts on geotechnical structures.

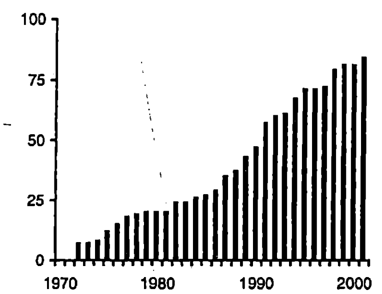

Figure 1a. Number of cumulative references (embankments)

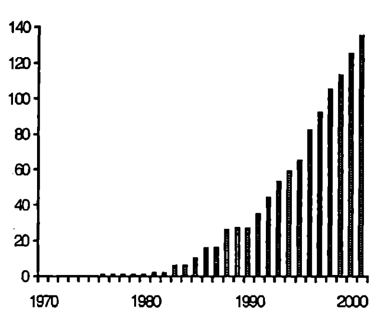

Figure 1b. Number of cumulative references (tunnels)

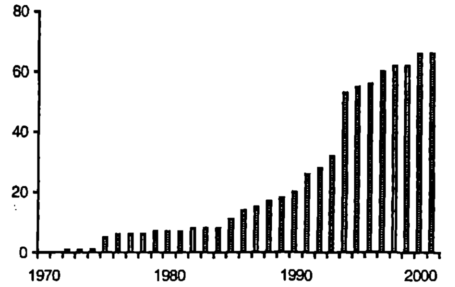

Figure 1c. Number of cumulative references (sheet-piles)

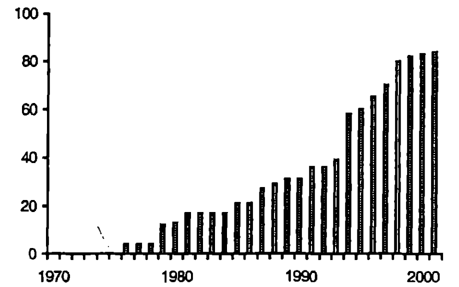

Figure 1d. Number of cumulative references (diaphragm walls)

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 complete quantitative data of the MOMIS database, relative to embankments and tunnels, have been published in the "Bulletin des Laboratoires des Ponts et Chaussées" (Mestat, 2001b and 2001c ; in French). Other papers are in preparation.

The displacements and other quantities were estimated from curves provided in the reference publications. Only a very small percentage of numerical values have been recovered directly from the papers.

3 MODELING OF RETAINING STRUCTURES

3.1 Geometrical model

Given that retaining structures quite often exhibit a much greater length than width, their performance is typically studied using a transversal section in plane strain (see Figure 2). Actual three-dimensional models prove to be very infrequent.

The data contained within the MOMIS database can serve to analyze, in statistical terms, the characteristics of meshes used in both vertical and horizontal directions for sheet-piles and diaphragm walls. Figure 3 shows the relationship observed between length of sheet-pile or diaphragm wall D and the total height of the mesh h. This height is the distance at which displacement boundary conditions have been imposed. It generally represents the thickness of the soil and, in rarer instances, the distance separating the surface from the natural substratum.

The ratio h/D varies between 0.85 and 4, with an average equal to around 2. Similarly, Figure 4 describes the relationship between the length D and the maximum model length L for a symmetric mesh (Figure 2). The ratio L/D lies between 1.2 and 14, with an average value of around 4.

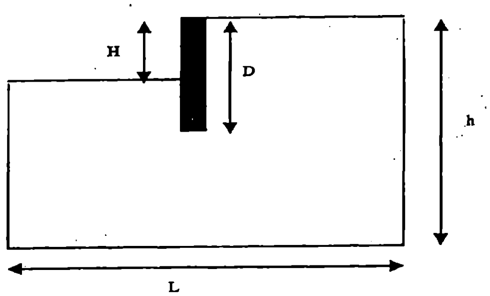

Figure 2. Characteristic dimensions of a transverse section of a retaining structure model

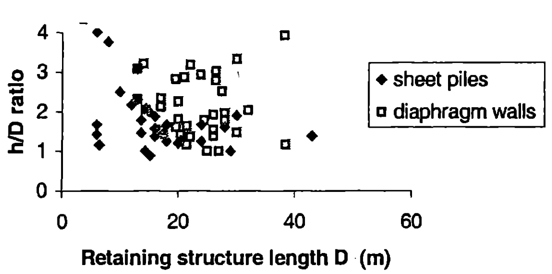

Figure 3. h/D ratio as a function of retaining structure length (extracted from MOMIS)

For those model set-ups which need not incorporate the presence of a substratum near the surface, obstacles or other interactions, this analysis serves to justify the minimum recommendations set forth for meshes and listed in publications (for example : Kulhawy, 1977 ; Mestat *et al.*, 1999):

$$h = 2\,D \text{ and } L = 4\,D$$

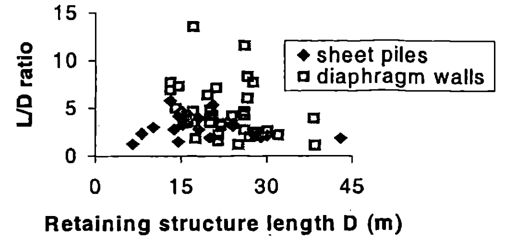

Figure 4. L/D ratio as a function of retaining structure length (extracted from MOMIS)

Enhanced computing power and capacity over the years has led to increasing the number of nodes taken into consideration in meshes. However, this increase is not as large as could be expected. As computation speed continues to rise, this advance does not only benefit the mesh; both the number of incremental steps, the modeling of construction and the complexity of the constitutive laws of soils also take demand a significant share of computation time requirements. The number of nodes in recent models has thus remained limited to approximately 1500 for a two-dimensional transverse section retaining structure mesh (which is also symmetric with respect to its axis) (figure 5).

It is difficult to accurately describe mesh density, given that authors tend to offer little comment on the choices inherent in carrying out geometrical discretization. Furthermore, in the publications, meshes are represented on highly-reduced scales, a feature that prevents from estimating the size of the smallest elements.

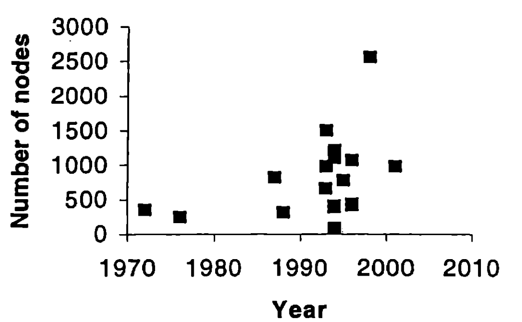

Figure 5. Evolution of number of nodes

3.2 Type of analysis for retaining structures

Three theoretical approaches are considered : undrained conditions (42%); drained conditions (48%) and consolidation (10%). From a historical perspective, the first two analyses preceded the third. Consolidation computations with non-linear behavior were not possible before the existence of high-speed computers, which first appeared towards the beginning of the 1980's.

The constitutive laws used for natural soils are essentially :

- linear and non linear elasticity (27%);
- elastoplasticity without strain hardening (50%);
- elastoplasticity with strain hardening (23%).

The part of elastoplasticity without hardening is important (Mohr-Coulomb or Drucker-Prager criterion associated with linear isotropic elasticity).

A comparison between modeling of embankments, tunnels and retaining structures shows a great difference in the types of analysis. The complexity of excavation sequence leads to using simple constitutive laws (perfect plasticity). The consolidation approach is rarer for tunnels and retaining structures. On the other hand the modeling of embankments on soft soil needs a strain hardening plasticity (for example, modified Cam Clay model) or elasto-viscoplasticity (Figures 6 and 7). Nevertheless the trend has favored use of strain hardening models.

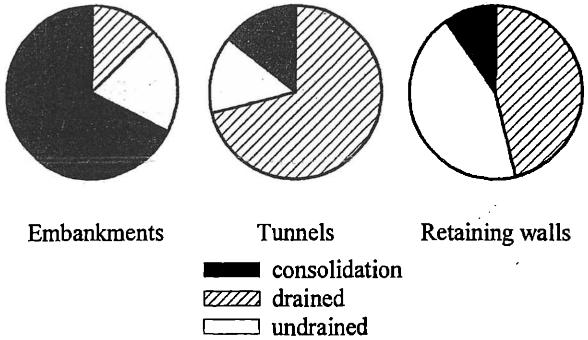

Figure 6. Type of analysis (MOMIS)

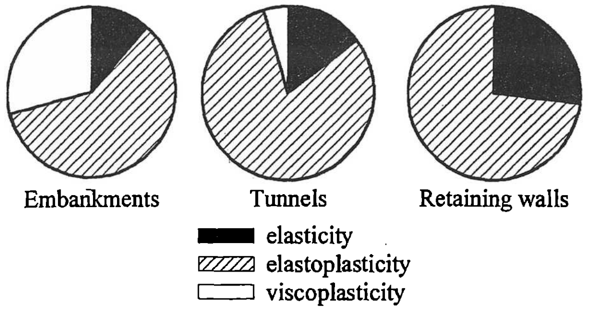

Figure 7. Type of constitutive laws used for soils (MOMIS)

The modeling of retaining structures is complex because of actual soil-structure interactions. Only 43% of FEM models stored in MOMIS use contact elements (zero thickness interface) or thin-layer elements. 57% of case studies were performed with the hypothesis of perfect adherence. Sometimes this hypothesis can be justified by the retaining system : for example, 73% of case studies contain several levels of struts. The computation follows the actual construction sequence.

3.3 Retaining system modeling

The retaining system can be simulated:

- by horizontal spring elements (7%). Nowadays this FEM approach is not used anymore;
- beam or shell elements (32%);
- solid elements (61%). The thickness of the "equivalent wall" varies between some centimeters (for example 5cm) and 20 centimeters (maximum). The strain modulus is back-calculated from the conservation of flexion rigidity.

The behavior of the sheet-pile or diaphragm wall is frequently isotropic and linear elastic.

On the other hand a strut may be represented by:

- an horizontal spring;
- a membrane element or beam;
- an horizontal displacement condition;
- an "equivalent" solid element;

and a ground anchor by:

- an inclined spring;
- a membrane element;
- a combination of spring and membrane elements.

4 2D FEM COMPUTATION-MEASUREMENT COMPARISON FOR SHEET-PILES

4.1 Comparisons with in situ measurements

Class A and C predictions were stored in MOMIS database (Lambe, 1973). Comparisons between measured and computed values were made at the end of construction. The parameters are:

- maximum horizontal displacement of the wall;
- maximum surface settlement behind the wall;
- forces in struts or ground anchors;
- bending moments in the wall.

At present we can investigate only the maximum horizontal displacement (Figure 8) and surface settlement (Figure 9).

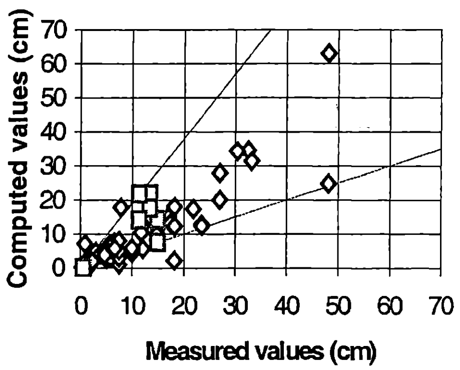

Figure 8. Comparison between the computed and measured maximum horizontal displacement of the sheet-pile at the end of construction (extracted from MOMIS). Squares represent class A predictions

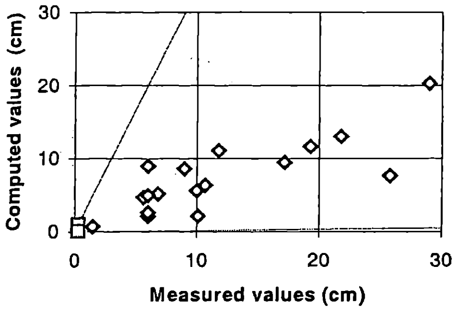

Figure 9. Comparison between the computed and measured maximum settlement behind the sheet-piles at the end of construction (extracted from MOMIS). Squares represent class A predictions.

4.2 Class A and C predictions

The references pertaining to class A predictions are relatively infrequent due to the extreme complexity involved in conducting such predictions. The results have been represented by squares in Figures 7 and 8.

Most class C predictions have led to relatively satisfactory results for the maximum horizontal displacement of wall at the end of construction (Figure 8). The points corresponding to computation values and measured values are primarily located within the boundaries defined by the results from class A predictions. 41% of the case studies stored in MOMIS database have a relative error which is less than 25% and 61% provide a relative error less than 50%.

The foregoing analysis makes no allowance for the specific geotechnical conditions. All the references available in MOMIS are represented in Figure 8.

The quality of predictions focused on the maximum surface settlement behind the wall is also acceptable (Figure 9). 13,5% of references give a relative error less than 25%. From a general standpoint, the models are not yet able to describe the surface settlements and often underestimate them.

5 ESTIMATION OF ERROR MODEL

The analysis of finite element model results and their comparison with *in situ* measurements has enabled quantifying the model error committed during the computations. This error is to be interpreted as the "sum" of the errors related to the software, its use, the approximated computation method and the approach employed to obtain the computational parameters. In deriving this error, class A predictions are obviously ascribed higher priority. Unfortunately, they tend to be rather rare (for our purposes, it would be desirable for their number to expand over the coming years). As a means of estimating model error, the entire series of references included in MOMIS database were taken into consideration.

For each variable and structure analyzed, the relative error was defined as the difference between the computed value and the measured value, divided by the measured value.

The previous analyses have considered relative errors with respect to the variables in an independent manner. An "effective model" however must be able to simultaneously predict all of the key aspects in the response of a geotechnical structure. Model error estimation must thereby take account of the entire array of measured variables (various displacements and pressures).

For sheet-piling problems, we may define a "cumulative error" which is equal to the sum of the absolute values of relative errors on surface settlements and horizontal displacements. For a computation-measurement comparison at the end of construction of sheet-piles, 4% of the models analyzed provide a cumulative error of less than 25% and just 16% show a cumulative error of below 50%. In contrast, 48% of the predictions reveal a cumulative error of above 100%. These errors are generated by the unsatisfactory numerical modeling of soil movements behind the wall.

The estimation of the error model (cumulative error) needs a more complete study. This paper is only a first step in the study of retaining structures. The work on the modeling of diaphragm walls is not finished.

6 CONCLUSIONS

The Geotechnical Structures Computations Unit of the LCPC has been conducting a "technology watch" mission over the past several years with respect to comparing finite element model results with measurements taken on actual full-scale structures. A wide array of articles, conference papers and research reports have been collated as part of this effort. The work performed by their authors in deriving prediction computations (class A or C) has led them to:

- considering the coupled performance of both the structures and their environment (e.g. soils, soil-structure interactions, pore pressures, creep); and
- introducing pertinent simplifications, select appropriate computation hypotheses, determine computational parameter values and make full use of current computing resources and theoretical developments.

The primary objective behind the technology watch program 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 model error.

The information extracted from the bibliographical analysis has been combined into a database called MOMIS. Collation of the references has served to identify a few general modeling rules (e.g. for the mesh dimensions) along with some worthwhile conclusions, such as:

- the elastoplastic laws without strain hardening remains the most widespread in representing the behavior of soil in retaining structure problems;
- the overall model error is less than 50% for the predicted horizontal displacement of the wall at the end of construction;
- the model error is high for the vertical settlement behind the wall, with a significant number of relative errors surpassing 100%;
- the "cumulative model error" lies on average in the 100% range at the end of construction. This high percentage is often due to the poor simulation of settlements behind the wall.

Other aspects concerning sheet-piled retaining structures and diaphragm walls may soon be open to analysis, such as the simulation of bending moments or heave at the bottom of the excavation or the determination of computational parameters.

Other prospective applications for MOMIS include the introduction of computation-measurement comparisons for foundation support structures and reinforced soils. Many references have already been gathered; it is now necessary to perform the appropriate analyses and extract the useful information. It can be projected that MOMIS will be expanding by some twenty new entries each year.

7 REFERENCES

Kulhawy, F.H. (1977) Embankments and excavations in Desai C.S., Christian J.T. (1977) *Numerical methods in geotechnical engineering*. McGraw Hill, 784 pages.

Lambe, T. W. 1973. Prediction in soil engineering. *Géotechnique*, Vol. 23, n°2, 149-202.

Mestat, Ph., Prat, M., Bisch, Ph., Millard, A., Pijaudier-Cabot, G. 1999. *Ouvrages en interactions*. Editions Hermès Sciences, Paris.

Mestat, Ph. 2001a. An overview on 25 years of numerical modeling of test embankments and tunnels. *Computer Methods and Advances in Geomechanics*, Desai *et al.* (eds.), Balkema, 1521-1526.

Mestat, Ph. 2001b. MOMIS : une base de données sur la modélisation numérique des remblais sur sols compressibles et sur la confrontation calculs - mesures in situ. *Bulletin des Laboratoires des Ponts et Chaussées*, n° 232, 43-58.

Mestat, Ph. 2001c. Validation des modélisations numériques d'ouvrages souterrains. Comparaisons avec des mesures de déplacements en surface et en profondeur. Base de données MOMIS. *Bulletin des Laboratoires des Ponts et Chaussées* (to be published).

Notes:

1. ISSMGE: International Society for Soil Mechanics and Geotechnical Engineering
2. IACMAG: International Association for Computer Methods and Advances in Geomechanics
3. NUMOG: Numerical Models in Geomechanics
4. NUMGE: Numerical Methods in Geotechnical Engineering.