Contribution of numerical methods in the education of geosciences: Implementation on two-tier study programs

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ABSTRACT: Numerical methods in engineering science have recently achieved great development following computer evolution. However, the use of advanced numerical modelling techniques in geosciences has not been used at a satisfactory level. There are many reasons for this, but most of them are related to the inadequate preparation of students, researchers and practising engineers in order to use such advanced tools. In this work we first discuss the importance of numerical methods in geosciences using recent literature as well as fundamental examples. A description of courses given in this area concerning engineering schools is presented. The minimum knowledge requirement for the training of numerical methods in geosciences is also discussed concerning with respect to both tutor and student. It can be shown that the teaching of numerical methods in geosciences is related mostly with second cycle degree programs and that there are efforts for implementation on the first cycle programs.

1 INTRODUCTION

Several physical phenomena are described mathematically from differential equations which can be ordinary differential equations or differential equations with partial derivatives. Few of these differential equations can be solved analytically mostly in cases where the geometry of the problem is very simple. This is the reason that from the beginning of the century efforts were made in the development of numerical methods (NM) for the solution of differential equations but recently achieved great development following computer evolution (Desai 1977).

The numerical methods are actually approximate algorithms of resolution of differential equations that can be easily found in various problems within mechanics. The more ordinary methods are those of finite differences (FDM) and finite elements (FEM). There are others, such as for example the boundary element method (BEM), the method of characteristics and prediction-correction methods. Nevertheless these methods are least popular in structural mechanics.

The FDM was practically the only numerical method which was used for the resolution of geotechnical problems prior to the appearance of the method of finite elements and their wide distribution. Lately the interest for this method was brought to light as it has important advantages for the simulation of specific scientific area of problems. In these problems the variable of time is important for their solution, as for example the flow and solidification or distribution of seismic waves (Bouckovalas 2006).

The FEM is considered to be one of the most important developments in civil engineering of the twentieth century (Papadrakakis 2001). Even though it was developed and applied for the static and dynamic analysis of structures, it is actually used in a wider category of problems in civil engineering as for example in fluid mechanics, thermodynamics, acoustics and seismology. In our days all the (advanced) computer programs that are used for the static resolution of a structure use the method of finite elements for their numerical simulation..

FEM has the advantage that it can be used for all types of problems and is accurate even if it is an approximate method. The method initially developed to solve problems considering linear material behavior (elastic), but now more complicated models can be used. Limitations of the usage of FEM (and NM in general) are concerning computational time as well as validation, verification and proximity of results (Papadrakakis 2001 and Jeremic 2006).

The solution of stress-deformation analysis of problems through numerical, computer-oriented techniques is becoming more and more popular in soil and rock engineering. The advances of numerical methods include solution of geometrically complex problems even in the presence of highly nonlinear material behavior and of media consisting of two or more phases, like saturated and partially saturated soils. Though, geotechnical problems that concern complicated geometry or infrastructures such as bridges foundation, underground work like tunnels, stability of grounds, seismic reaction of foundations etc are solved mostly using computational methods (Kavvadas 2005a and Bouckovalas 2006).

In the above mentioned reference a first fundamental example of the use of NM is presented. It is stated that in tunnel engineering NM are the more accurate methods depending on how well we have defined the sites' geology and material. Another example is also presented in Felice (2005) where the described project was a simple addition to an existing structure and it is noticed that the use of a commercial NM code was imposed for the existence of a safe and economic solution.

The importance of NM in large or mega sized projects (underground works, off-shore works) is well established in general as mentioned in earlier paragraphs. In medium size projects, NM can help in better understanding of the performance of a structure during construction and throughout its service life (Muir Wood 2005)

Even in small sized geotechnical projects, like a building foundation, the use of numerical methods is sometimes necessary. This includes beam-foundations using Winkler model which can be solved using other methods than NM only in specific cases (Kavvadas 2005c). It is also an option in simple problems (i.e. where only shear stress appears or flow problems) where elasticity cannot describe all the observed phenomena (dilatation, change of pore pressures) (Kavvadas 2005b), in general.

On the contrary advanced theories and latest developments in geosciences (non-linear models, gradient theories, dynamic soil-structure behaviour, coupling models) are already implemented in numerical software (Arulmoli 2005, Vardoulakis et al 2005, Oka 2005). It must be noticed that most of the latest developments evolve mostly FEM. In the mathematic part of the method, focus is given on precision and stability of the algorithms as well as computation time (Borja 2005) and on implementation of probabilistic tools in FEM (Griffiths 2005).

However, the use of advanced numerical modelling techniques in geosciences has not been used at a satisfactory level. Felice (2005) states that NM are still viewed as an 'unneeded expense for software that will see minimal use and require expensive training with a limited return on a practices' profitability'. In the same point of view Arulmoli (2005) notices that 'Practicing geotechnical engineers are faced with challenges from different fronts including limited budgets and demanding schedules; clients, owners, and reviewers who are not well-informed about the benefits of advanced computer programs or who are unwilling to accept tools or methodologies that have not been proven in the industry'. There are also some reasons that existed a few years before but now are no longer exist like the non user-friendly environment of available software (Sakelariou et al 1999). Many authors agree that most of the reasons that have caused the lack of use of NM are related to the inadequate preparation of students, researchers and practising engineers in order to use such advanced tools (Jeremic 2005, Felice 2005, Muir Wood 2005).

In this work education in numerical methods are concerned in 1st and 2nd cycles of higher education in CE. In the previous paragraphs we presented the importance of the numerical methods in civil (structural) engineering and even more in geotechnical engineering based on recent literature and some fundamental examples. Recent developments are also presented through literature. In the next paragraphs, the implementation of NM in European CE schools is tested. A research in the study programs of the European schools that participate in EUCEET III, concerning NM, is presented and commented. Description of courses concerning NM is also presented. Then, the necessary background for students, researchers and practising engineers is presented for every part of studies also based in the above mentioned research. Finally conclusions are presented and a proposition is made for the implementation of the NM in education and subsequently in practice.

2 RESEARCH DESCRIPTION AND RESULTS

2.1 *Research concerning NM in the European (Civil Engineering) study programs*

This research includes the 72 educational institutes (EI) of the 105 institutes participating in EUCEET III. The resource of the research was the information that every Civil Engineering (CE) institute provides in its internet site. Every course related with numerical methods was distributed according to the cycle that was offered and a category that created by the authors. For this work we created three categories of courses: a) Introductory courses in

numerical analysis (IC) b) Courses evolving NM in structural engineering in general (SC) and c) Courses evolving NM in geotechnical engineering or other geoscience (GC).
It must be acknowledged that research is limited in languages (English, French, German, Greek). There are schools which give courses in English only in some of the levels (cycles) so information is given only in this area. There are also schools which NM (in all categories) are autonomous course or part of another in all above categories. Both were included in the research.

In study programs that 1st and 2nd cycles are not discrete separated (5 year programs), the first 4 years are regarded as the 1st and the last as the 2nd. Another important notice is that 2nd cycle programs that are specialized in geosciences have one or more GC. It must be also noticed that distribution of courses in compulsory, elective or facultative is not made in a quantitative manner. But, in general, IC are usually compulsory courses and SC and GC are usually elective or facultative courses. SC and GC are compulsory in 2nd cycle study programs specialized in the area (Post graduate programs in Structural or Geotechnical (Geoscience) Engineering respectively).

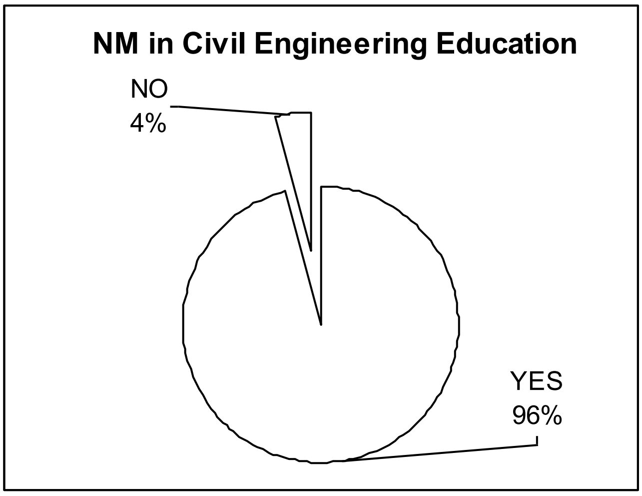

Figure 1. Pie figure concerning percent of EI teaching any lesson concerning NM or NA in CE studies

2.2 *Results - Comments*

Results are presented in terms of pie figures. A first general result that can be obtained from Figure1 is that almost all CE Departments have at least 1 course evolving NM or Numerical Analysis in general. The minority of 4% consists of Institutes that CE follows a rather Project management direction.

In Figure 2 can be seen that the majority of the EI accepts the importance of NM in any level and includes them in the study programs. Comparison of Figure 1 with Figure 2 shows that 10% of the Institutes do not include any lesson in the 1st cycle of studies. These are Institutes that still consider that NM and Numerical Analysis in general can not be a fundamental part on CE studies. They consider it as special knowledge that must be taught in 2nd cycle study programs.

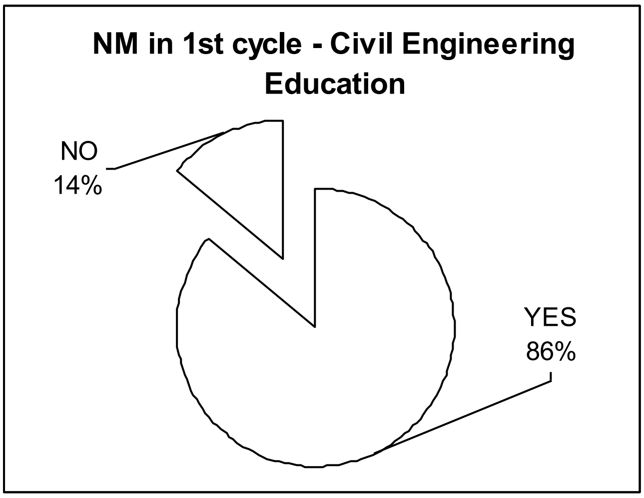

Figure 2. Pie figure concerning percent of EI teaching any lesson concerning NM or NA in the 1st cycle

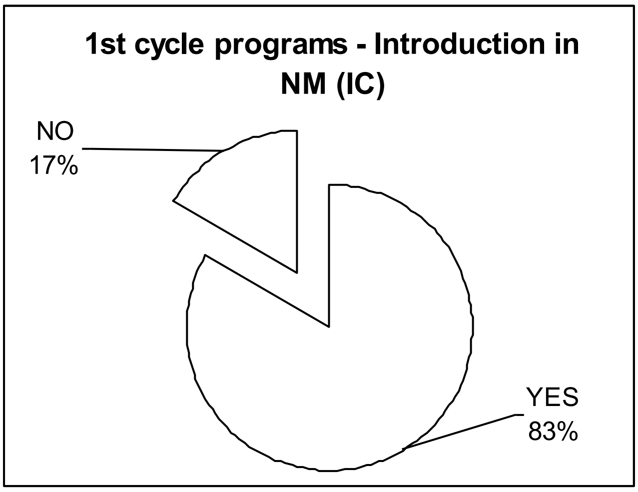

Figure 3. Pie figure concerning percent of EI teaching Introductory courses concerning NM or NA in the 1st cycle

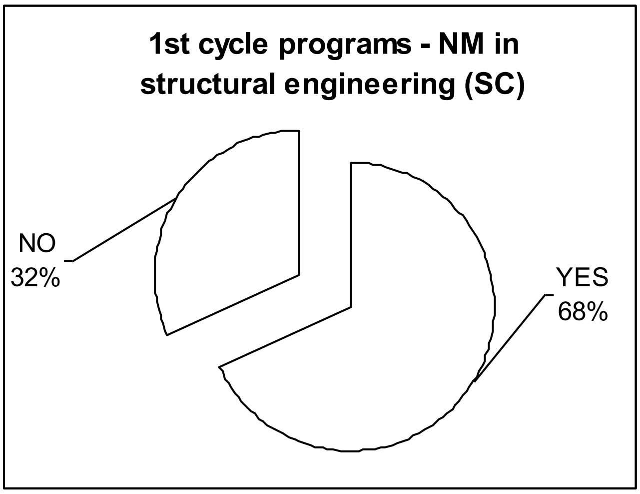

Figure 4. Pie figure concerning percent of EI teaching Structural Courses concerning NM in the 1st cycle

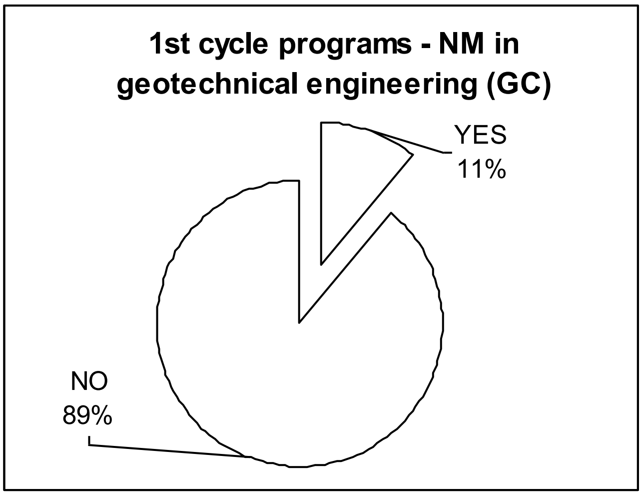

Figure 5. Pie figure concerning percent of EI teaching Geotechnical Courses concerning NM in the 1st cycle

Figures 3, 4 and 5 show the results following the categorization of the course in the 1st cycle. As can be seen in Figure 3 the majority of EI has an introductory course in NM (which is quite a significant percentage) however there is a 17% of them which do not include one. Comparing Figure 2 and 3 the 3% of EI consider introduction to be less necessary therefore they add it at the beginning of the other course's categories or they have them in both cycles (1%).

The results of an in-depth analysis of the presence of more specific NM courses in the 1st cycle are shown in Figure 4 and 5. As Figure 4 shows 68% of EI includes in their study programs NM in structural engineering and 32% does not. This shows that the majority of EI accepts the importance of teaching NM in structural engineering. However the decrease of teaching NM on specific applications is expressed by the 89% of EI that do not involve NM in geotechnical engineering in 1st cycle programs. Only 11% of CE departments in EI regard NM in Geotechnical Engineering as a fundamental course. Comparison of Figure 4 and Figure 5 shows the importance for the EI of NM in SC and GC: a difference of 57% is noticed.

Figure 6 in comparison to Figure 2 shows that there is a 42% which includes introduction on NM only in the 1st cycle. The other 44% of EI includes NM in both cycle programs. These observations are included where NM in every cycle of EI is presented.

From Figures 3 and 8 it can be seen that most of the IC are included in 1st cycle, which is an expected result since introductory lessons should be given in the fundamental studies. Apparently there are more than 1% has IC in both cycles and in the same way more than 11% that have SC in both cycles. Comparison of Figs 4 and 9 shows that SC are considered a fundamental course in CE since it is offered in the majority of EI in the 1st cycle. However knowledge of SC can be enhanced also in the 2nd cycle programs (43%).

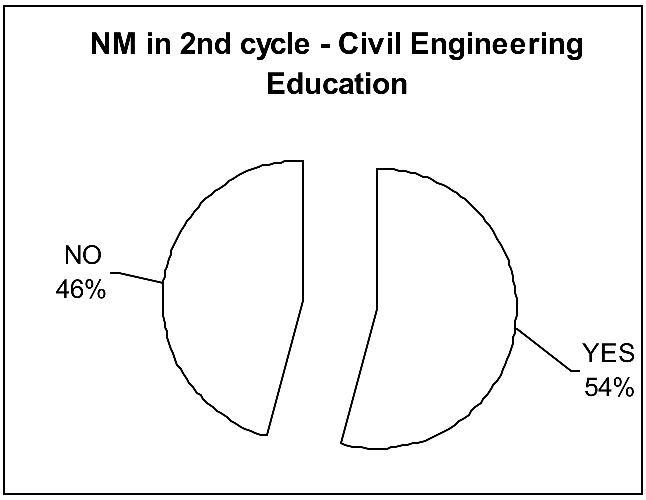

Figure 6. Pie figure concerning percent of EI teaching any lesson concerning NM or NA in the 2nd cycle

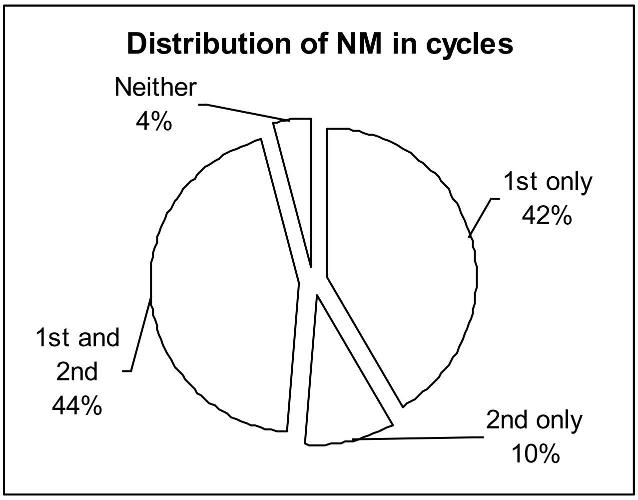

Figure 7. Pie figure concerning percent of EI teaching NM

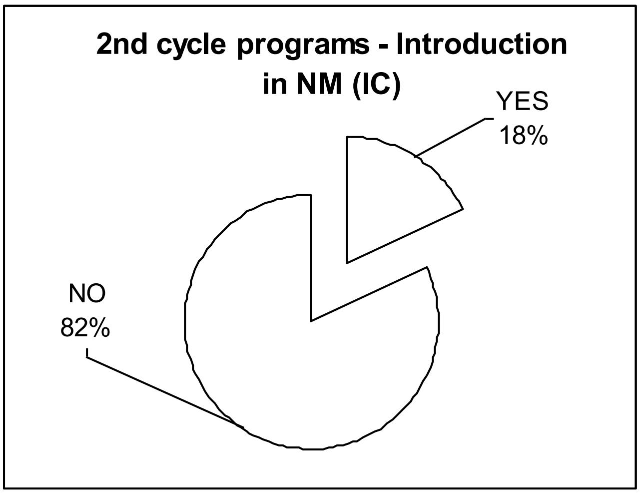

Figure 8. Pie figure concerning percent of EI teaching Introductory courses concerning NM or NA in the 2nd cycle

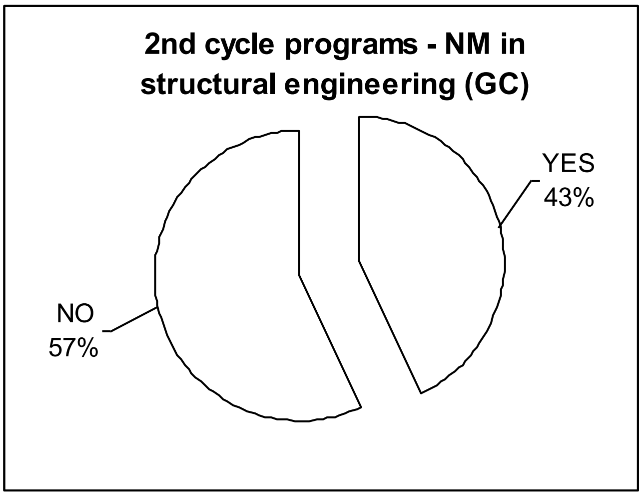

Figure 9. Pie figure concerning percent of EI teaching Structural Courses concerning NM in the 2nd cycle

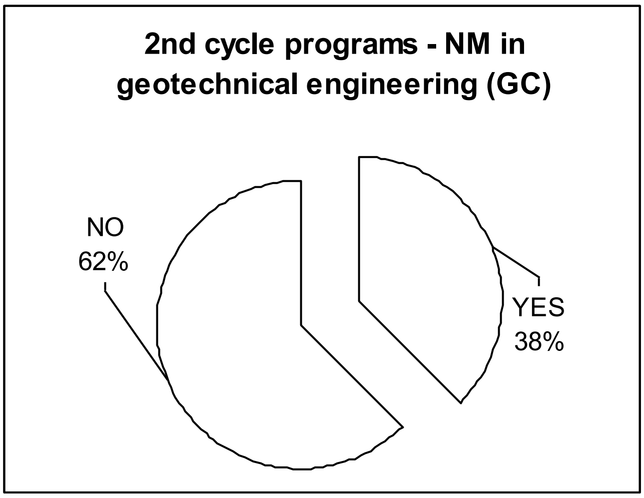

Figure 10. Pie figure concerning percent of EI teaching Geotechnical Courses concerning NM in the 2nd cycle

As far as GC are concerned, comparing Figure 5 and 10 can be claimed that specialized knowledge regarding NM and geotechnical engineering can be acquired in the 2nd cycle at most since it is offered in more than . It is possible that EI consider it as a specialized course that is a Since the basic knowledge has been gained either in the 1st or 2nd cycle, most of GC can be taught in the 2nd cycle.

3 TRAINING OF NUMERICAL METHODS FOR CIVIL ENGINEERING EDUCATION

3.1 *Introductory courses*

The students are supposed to know elementary part of mathematics like error analysis, approximation, Taylor-expansions, integration and derivation. Among the topics of the course are interpolation and the least square methods. Also numerical derivation and integration, non-linear equations and system of equations, numerical solution of ordinary and partial differential equations are included. Learning activities should include programming applications. The idea of the course is to make the students able to develop, implement and analyse certain numerical algorithms. Recommended previous knowledge includes basic calculus, vector calculus, linear algebra and geometry and some basic programming experience

The above described course with minor differences is included in all study programs with introductory courses. Other introductory courses follow the previous course and include numerical solution of differential equations. This kind of a course concerning the method of finite differences usually includes: difference operators, difference schemes for a variety of equations, Analysis with respect to consistency, order, stability and convergence. Also solution of linear equations, in particular iterative techniques and preconditioning is contained.

A course concerning numerical solution of differential equations using finite element method usually includes: minimization principle, weak formulation, boundary conditions, quadrature, error analysis, stability, convergence, implementation, direct and iterative solution of the resulting algebraic system of equations, and applications.

Above mentioned courses are considered introductory courses and contain the mathematical background of the NM. Necessity of the courses will be discussed later in this work.

3.2 *Structural Courses*

In this paragraph Courses evolving NM in structural engineering in general (SC) will be considered. It should be mentioned that the line separating Introductory from Structural courses is not well established since there are courses that can be included in both areas. For example courses evolving the theoretical foundation of finite element methods (FEM) and skills in the use of FEM for stress analysis of linear elastic structures are subject to static loading conditions. The content of such a course would contain: One-dimensional elements and computational procedures, theory of elasticity, principle of virtual displacements, two- and three-dimensional elements, variational principles (principle of stationary potential energy, strong form and weak form of a physical problem), isoparametric elements and applications of the finite element method to linear-elastic two- and three-dimensional structures.

An extension to the structural part would be a course that blends underlying theory with application providing a practical understanding of the finite element performance. Also theoretical foundation of the finite element method with emphasis on design and performance of various finite elements for analysis of beams, plates, shells and axisymmetric structures can be included. The course should also give an introduction to error estimation and adaptivity. The coverage also should include an introduction to geometrical modelling.

Practicing the NM in structural engineering could be followed by a course that includes finite element discretisation via weak form formulation of the differential equations. The main applications could be 2- and 3-dimensional field problems in elasticity and heat conduction. Dynamic problems, nonlinear problems as well as modern multi-physics formulations will also be addressed.

Finally advanced topics in structural modelling and analysis should contain establishment of methodology for finite element modelling and analyzing structures, with respect to design according to limit state principles, with due account of relevant loads. Topics could be: modelling and linear elastic analysis of stiffened panels and shells as well as global behaviour of ships and platforms. Assessment of error sources in the structural analysis dependent upon the mathematical modelling of loads and structure, discretization and round-off errors in the finite element model, introduction to nonlinear static and dynamic analysis of structures with geometric nonlinear and elasto-plastic behaviour.

Special courses in this area can be given (with extension in referred areas) in non-linear finite element analysis which can include: classification of nonlinearities (geometrical, material and boundary conditions), strain and stress measures for large displacements/deformations, mathematical models for elastic and elastoplastic materials, geometrical stiffness and linearized buckling, formulation of the nonlinear finite element method, Numerical integration of dynamically excitated systems, implicit/explicit time integration, Incremental-iterative solution methods for nonlinear static and dynamic problems, modelling of nonlinear boundary conditions, impact and contact problems.

Another special course could be a computational methods in structural dynamics course. The course could cover description and modelling of the dynamic properties of structures, methods for the calculation of dynamic response in time and frequency domain, analysis of free vibrations, and dynamic stability. A short presentation of wave propagation related to structure and foundation interaction is included. For the calculation of dynamic response induced by randomly distributed loads stochastic methods are presented. Applications will be taken from wind and earthquake engineering, as well as impact and explosion type of events.

As can be seen from the above mentioned courses almost all of them concern finite element method and only one concerns other methods. Another comment is that focus on exercises in the above courses should include usage of several well-known software in the area.

3.3 *Geotechnical (Geoscience) Courses*

These kinds of courses differ according to the geoscience that they are applied to. A course in Geotechnical Engineering should include the basis for practical use of the FEM in geotechnical design. The theoretical background of the method is briefly already covered. Focus is primarily on basic understanding of soil behavior, problem definition, determination of input soil parameters, evaluation of computed results and comparison to hand calculated estimates. The numerical analyses will cover bearing capacity and settlement of simple and complex foundations, slope stability, retaining structures and buried pipelines. Seepage of water and consolidation with time are dealt with.

Numerical modelling for rock engineering should include basic knowledge of numerical analysis regarding this topic. Several numerical methods will be introduced, such as FEM, DEM and FDM. The aim is students to understand the fundamental theory and application of the numerical methods to rock engineering. Popular commercial codes will be used in exercises. The course is carried out mainly in guided self-study and a project report shall be submitted.

It must be noticed that focus on exercises in the above courses (as also in SC) should include usage of several well-known software in the area.

3.4 *Minimum knowledge requirement*

The theoretical background for most computer methods that are examined in courses is extensive and it cannot be covered in the frames of only one course and for this reason more undergraduate and postgraduate courses are needed for the detailed description of various computational methods for a minimum level of the education needed for the use of NM.

However, we can notice that almost all EI agree that technology and evolution imposes at list 1 course in Introductory and Structural area of NM in the main part of studies (1st cycle) as seen in the above research. In the 2nd cycle of CE studies EI (in general) have more than 1 SC which is satisfactory in this level. Consideration should be given in the necessity of IC in the 2nd cycle and GC in both cycles.

The first part of the above mentioned statement can be ignored since IC can be found in almost all of the CE schools. In this paragraph we will focus on the second part. Felice (2005) gives the point a view of practising engineers and states that the new project delivery systems will make the knowledge of (the use of) NM in geotechnical engineering, necessary, in all sizes of projects. This statement can be used together with a major part of the Introduction to support the statement of necessity of GC in the fundamental part of studies and subsequently in the 2nd cycle.

4 CONCLUSIONS - PROPOSALS

Recently, (2005), a workshop took place in Maryland, USA, where the main topic was the implementation of non-linear modelling of Geotechnical Problems in practice. Modelling of non-linear or other constitutive models and gradient theories is usually connected with NM. Also implementation of the advanced modelling in practice passes through education and training. Subsequently, proposals of important people in the area (most of them academics) must be considered. Some of them are in the following paragraph.

Desai (2005) proposes better interaction between practice and theory, between construction, design and research. This proposal is fundamental for the broadness of the NM in general. Hueckel (2005) proposes teaching undergraduate students basic plasticity models, including Cam Clay, encourage the use of numerical analyses using Finite Element Methods in the undergraduate geotechnical engineering classes, encourage the use of mathematical modelling in the graduate geotechnics (not only geomechanics) classes as a part of required (core) course education, find the ways that major industry and research stimulate the development of new and use of the existing advanced mathematical models. This opinion is in the area of the suggestions made by Desai (2005) in more detailed form. Muir Wood (2005) proposes implementation of recent developments in Geomechanics in 1st cycle programs, using simple terms. A practicing engineer Felice (2005) as mentioned earlier states that NM concerning Geotechnical Engineering will be necessary in the near future and focus must be given in the broadness and the conditions for the usage of them.

As far as this work is concerned we can summarize the following:

- Numerical Methods are a fundamental part of Civil Engineering studies in European Academic Institutes
- European study programs include mostly Introductory and Structural Courses in the fundamental studies and mostly Structural Courses in 2nd cycle studies
- Geotechnical Courses are mostly related with 2nd cycle study programs in It is necessary to implement Geotechnical Courses concerning Numerical Methods in 1st cycle programs.

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