Although I will be formally retiring at the end of June 2008 and do not want to influence my successor, assuming there will be one, I can still discuss the advantages and disadvantages of potential options of the organisation for the Chair on soil mechanics being successful.

In this context I could come across questions like: Why would soil mechanics still be needed in Civil Engineering at Delft? Why would geo-engineering be the better engineering application topic for organising the education and research on soil mechanics? Why would the Department of Geotechnology give the best opportunities for stimulating education, research and application?

IS SOIL MECHANICS STILL WORTH A CHAIR?

FRANS MOLENKAMP

When I arrived at Delft in 2002, after 12 years at a similar position at the University of Manchester, I was requested to consider such kind of questions too. With hindsight I guess that elsewhere and upthere in the organisation of Delft University the answers to such questions had already been formulated, but that was short term university politics, which changes in time as people move on to other positions and retire, like I will soon. At the end the education must attract the best students, who can serve society in the best possible way, while the research must be done in an environment offering the best possibilities for opening new pathways, improving the soundness and the width of applicability of models for validating engineering designs and processes. I assume that in the long term it is the effectiveness, efficiency and quality of service to society that determine the success and continuation of soil mechanics as a separate academic education and research field, which implies that soil mechanics may remain a Chair topic as long as the Chair can pose and address new faculty-wide research questions on soil mechanics and support university-wide application.

However, before addressing any questions first the profile of soil mechanics should be defined. This presumes that such profile does exist and is unique. To find out whether or not that would be the case I could imagine that one could interview a number of world leaders on soil mechanics. If this would lead to one coherent profile, the case would have been made properly. The only possibility for me is to continue this consideration, while assuming that I can give a reasonable description of soil mechanics as an academic field.

FIGURE 1 FIELD INVESTIGATION. SHERBROOKE SAMPLING AT VINKEVEEN DURING FIELD CAMPAIGN BY IR. F.A.J.M. MATHIJSSEN IN 2006 AND 2007.

On that basis first the optimum education programme for soil mechanics will be formulated and argued and subsequently an attempt will be made to list the currently recognised main research topics. Finally some options for optimizing the success of soil mechanics as an academic field will be put together and evaluated by comparing advantages and disadvantages.

PREFERRED EDUCATIONAL PROGRAMME FOR SOIL MECHANICS

Soil mechanics provides the basis for evaluating the suitability of many types of civil engineering structures and both agricultural and engineering mechanical processes. To clarify this role first the chain of activities for arriving at such evaluations is reviewed. Subsequently the required teaching modules for the academic education on soil mechanics are described.

The chain of activities, leading to the evaluation of the suitability of a structure or a process, involves:

1 Rough preliminary design for recognising potentially governing conditions for the structure or process.
2 Global insight into the possible severity of the heterogeneity and history of the available materials, often concerning the geology and history of site and region
3 Design and execution of data collection campaign, involving usually cone testing, boring, soil sampling and in-situ testing.
4 Laboratory investigation to determine the magnitudes of the parameters of the existing relevant material models.

5 Evaluation of suitability of structure or process by means of various tools, depending on both its level of novelty and its capitalised value. For simple common structures and processes semi-empirical evaluation methods may often suffice, while for novel and expensive projects at least computational tools and possibly model tests will be needed, while for stage-wise constructions and on-going processes the observed behaviour may be used for control and improvement of performance.

To prepare the undergraduate civil engineering students for the wide application field of soil mechanics, to make them aware of the remaining range of limitations and lack of understanding, to enthuse them for handling such limitations as part of their Master projects and possibly for subsequently tackling the most urgent research questions as PhD, the educational programme should contain the following modules:

1 Basic Engineering Geology to become aware of the relevance of the geological history for the mineral characteristics, the state of the soil skeleton and the applicability for many geo-structures and processes.
2 Overview of basic soil mechanics, groundwater mechanics and general geotechnical engineering techniques, leading to the appreciation and application of design rules.
3 Continuum geomechanics to describe and select appropriate types of mechanics (drained, undrained, consolidation, dynamics, flows, unsaturation, heat), material models (elastic, plastic, elasto/hypo-plastic, elasto/hypo-visco-plastic) and related failure mechanisms (continuous/localized shear, fracture, crushing).
4 Micro-mechanics in support of the development of continuum models of porous/granular materials and common pore fluids (water and air).
5 Experimentation at continuum and micro scales to establish material behaviour and behaviour of structures and processes.
6 Analytical and numerical geomechanics, including dynamics, to get insight into the dependence of the capabilities and limitations of the analytical and numerical models on both the approximate numerical methods and the mathematical models of continuum geomechanics, materials, failure mechanisms, large flow etc. This also enables the appropriate problem-dependent selection of analytical and numerical models and the appropriate interpretation of the resulting predictions.
7 Visualisation of the computational and experimental results of the behaviour of materials, structures and processes on both the micro- and continuum scales.
8 Analytical and numerical stochastic and invers modelling to reduce engineering risk and improve control by accounting for the geological variability of the stratification, the heterogeneous nature of soil characteristics and the observations of deformation, failure and flow processes for improved numerical model predictions.
6 Support of teaching of the ever-growing range of techniques and design rules for all relevant application fields of soil mechanics, both within the geo-engineering section and faculty-wide. Concerning the latter several application fields of soil mechanics can be recognised like: Hydraulic Engineering with e.g. dykes and hydraulic structures, Road- and Railway Engineering with e.g. embankments, Construction with e.g. buildings, towers, bridges, tunnels and Offshore Engineering with e.g. offshore structures, anchors, pipelines. Strong involvement of the institutes and industry in the teaching of techniques and design rules will guarantee sufficient attention to the many practical engineering aspects as well.

The first two topics of the above list of teaching topics must be suitable for the BSc programme, while the remainder should form at least a specialisation of a Master programme, which should enable the teaching of about 300 hrs for topics three to and including eight. Topic nine should concern several application fields, the teaching of which should be shared with the corresponding sections and involve significant contributions by practising engineering experts, well aware of the latest techniques and standards.

MAIN RESEARCH TOPICS IN SOIL MECHANICS

The research in soil mechanics can be subdivided roughly into three components, namely:
1 the activities in the field and laboratory,
2 the modelling and
3 the prediction by analysis and physical model testing. As the modelling and laboratory testing are intrinsically connected, they may be best discussed together.

Due to the ever-growing versatility of computers and the capabilities of models, the research emphasis on prediction is expected to keep on shifting towards numerical analysis, although prediction by model testing may remain important for a long time. In addition, despite the required extreme simplifications of the analytical problem definitions, the analytical solution methods are expected to remain essential due to their accuracy, probably even beyond the times that soil mechanics will be understood completely.
In the following three sections the currently foreseeable needs for research on these aspects will be reviewed.

1 SAMPLING AND FIELD TESTING

For sampling of peat and other very soft soils the 'sherbrooke sampler' seems to become also slowly accepted in The Netherlands *(see figure 1)*.
Sampling of loose sand is still problematic in the Netherlands. Research on liquefaction in Japan and Canada suggests possible improvement by combining in-situ freezing and coring.
The in-situ horizontal effective stress distribution, possibly anisotropic as in Pot-clay and an important component of the 'initial state' of the ground, may be measurable by means of the self-boring 6 load-cell -pressure meter.

Determination of the variability of the stratification and heterogeneity of soil deposits by means of traditional methods, involving mainly vertical line data, is very expensive, particularly for getting insight into the horizontal distribution. Combination of various geophysical methods may lead to more economical techniques.

2 DETERMINATION AND MODELLING OF MATERIAL BEHAVIOUR

2.1 CONTINUUM MATERIAL MODELS

Although process formulation still needs further attention, in particular for unsaturation *(see figure 2)*, probably the larger shortcoming of soil mechanics concerns material modelling. Generally recognised shortcomings involve a.o. monotonic, alternating and rotational loading, contraction and liquefaction, pre-loading and creep, anisotropy, structuring and de-structuring, high isotropic stress range and crushing, hydraulic and thermal processes for pendular unsaturation and cyclic swelling and shrinkage due to repeated saturation and desiccation. For instance, both the peculiar shortcoming of non-associative elasto-plastic models and the limited accuracy of hypo-plastic models drastically limit the quality for dilative granular materials to describe important aspects of their observed behaviour even for monotonic deformation and therefore need further attention.

Experimental limitations are mainly due to lack of appropriate laboratory apparatus, development of which forms an intrinsic part of research. An axial-shear apparatus *(see figure 3)* may enable to measure the anisotropic stiffness and strength of fibrous peat soils. A thin-wall hollow-cylinder torsional-shear apparatus may be used to determine the mechanical effects of principal stress rotation, which is essential for the validation of the modelling of this aspect.

2.2 MICRO MATERIAL MODELS

To develop continuum geomaterial models with vectorial and tensorial state parameters of soils granular micro-models are necessary. Such micro-models need to be validated by comparing model simulations with observations of micro experiments. Subsequently corresponding continuum models can be developed, taking full advantage of the capabilities of the proven micro-models. For this research the existing photo-elastic facilities may prove to be useful, but for the micro-experiments also new apparatus and access to existing international research facilities may be needed.

For instance micro-hydro-mechanical measurements of unsaturated granular packings by means of tomography using X-rays and synchrotron should be suitable to validate numerical simulations of these processes at the micro-scale. These data should enable to derive representative vectors and tensors of 'anisotropy", 'fabric' *(see figure 4)*, 'tortuosity' and 'stiffness". The numerical simulations will also enable to determine, by inversion, the corresponding inter-particle friction and cohesion and the decomposition of the inter-particle movements by sliding, rolling and rotation. Finally both the validated hydro-mechanical micro-model and the composed micro-experimental data base can be used to validate continuum formulations of the hydro-mechanical processes, which should include evolution rules for the vectors and tensors as well.

2.3 FAILURE MECHANISMS

In geomaterials one common failure mode, namely 'drained shear planes", often gradually develop from

FIGURE 2

MODELLING OF EFFECTS OF CAPILLARY ACTION - HYDROSTATIC STRESS STATE IN UNSATURATED SOIL COLUMN. DISTRIBUTIONS VERSUS DEPTH z OF THE PORE WATER STRESS p^w, THE PORE GAS STRESS p^g AND BACKGROUND STRESS p^b, THE DRY AIR STRESS p^{ga}, THE EXPRESSIONS $p^g + \psi\chi$ AND $p^x + \psi^x X_{zz}$ FOR ILLUSTRATING THE COMPONENTS OF THE *SUCTION-INDUCED VERTICAL INTERGRANULAR STRESS* $\psi^*_{zz} = -\psi X_{zz}$, THE VERTICAL TOTAL STRESS σ_{zz}, THE *CAPILLARY PORE SUCTION* ψ AND THE *VERTICAL INTERGRANULAR STRESS* σ_{zz} FOR *PRIMARY DRYING* OF AN UNSATURATED HYDROSTATIC SOIL COLUMN WITH ONE METRE HEIGHT AND COMPOSED OF SILTY SAND WITH $d_{50} \approx 100\mu_m$. ALSO THE CAPILLARY RISE h^c IS INDICATED.

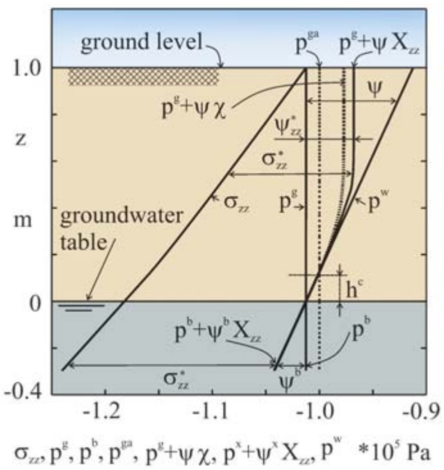
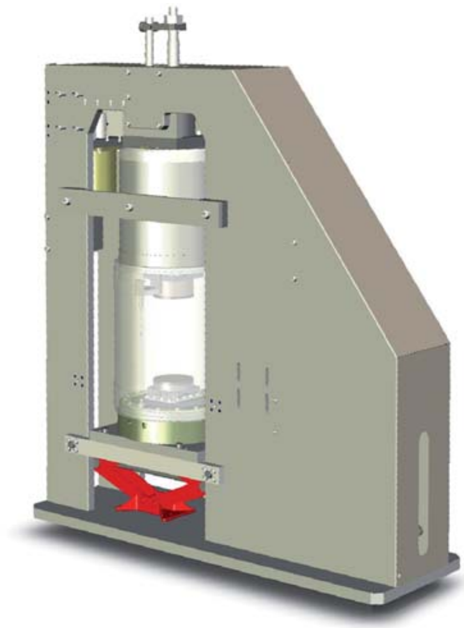


FIGURE 3

LABORATORY INVESTIGATION. DIRECT-SIMPLE-SHEAR AND AXIAL-SHEAR APPARATUS FOR THE MEASUREMENT OF THE ANISOTROPIC STIFFNESS AND STRENGTH OF SOILS AS DEVELOPED IN COLLABORATION WITH GDS IN 2008.



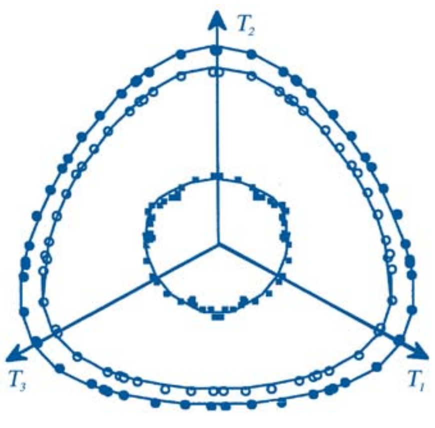


FIGURE 4

MICRO-MECHANICAL MODELLING AND NUMERICAL SIMULATION OF BEHAVIOUR OF GRANULAR PACKINGS. PEAK DEVIATORIC STRESS STATES IN THE π-PLANE IN PRINCIPAL STRESS SPACE FOR RADIAL DEVIATORIC LOADING OF AN *INITIALLY DENSE PACKING OF SPHERES* AT A MEAN STRESS OF 100 KPA. THE BLACK DOTS ● INDICATE THE DEVIATORIC PART OF TOTAL STRESS TENSOR $\acute{\sigma}$, THE OPEN DOTS o CHARACTERIZE THE DEVIATORIC CONTRIBUTION BY STRESS TENSOR $\acute{\sigma}^N$ DUE TO THE NORMAL CONTACT FORCES AND THE BLACK SQUARES ■ DENOTE THE DEVIATORIC PART OF THE CORRESPONDING *FABRIC STRESS TENSOR* $\acute{\sigma}^A$ (THORNTON, 2000).

a spot with local weakness and propagate through the material to form a shear plane, cutting a failure mechanism from the soil volume. The propagation of the shear plane and the subsequent creeping or dynamic motion of the failing soil volume are still important research topics *(see figure 5)*.

A second failure mechanism, requiring further attention, concerns liquefaction, when water-saturated loose sand becomes unstable and starts to flow in a dynamic way as a dense frictional liquid *(see figure 6)*. Subsequently during flow this liquid may solidify due to consolidation leading to re-sedimentation.

A third failure mode of research interest concerns the brittle cracking of cohesive soils due to stretching and resisted shrinkage, where also unsaturated fine granular soils can be considered as cohesive by capillary action. Both the first ‘shearing’ and third ‘cracking’ failure mechanisms are common for all geomaterials, including concrete, and are therefore very suitable for collaborative research programmes involving also concrete engineering and computational mechanics.

Another deformation and failure phenomenon, requiring further research, concerns the interface between soils and rough rigid walls and/or reinforcing geotextiles, where provisionally the initiation and growth of relative slip seem to be similar to observed behaviour of shear planes.

At the interface between submerged steep slopes composed of dense sands and the free water the micro-stability of the soil can be lost, leading to the phenomenon of breaching, where individual sand grains loose their stability and start to slip and role down the slope, by doing so driving a density current of a water-sand mixture with erosive capabilities, affecting the lower part of the slope. Clearly, this instability phenomenon involves both soil and fluid mechanics in interaction and warrants further attention amongst others due to its relation with accidental human-induced tsunamis.

Observations of failures in both geo-centrifuges and large-scale model tests enable the validation of calculated failure modes. For the validation of models for the initiation and gradual propagation of specific failure mechanisms at the micro-scale more specific experiments may be needed.

2.4 CAPILLARY INTERACTION BETWEEN SOIL SKELETON, PORE WATER AND PORE AIR

In the Netherlands the behaviour of unsaturated soils has hardly been investigated yet. The capillary interaction between water, air and soil skeleton can provide for a significant apparent cohesion, e.g. affecting the strength of the unsaturated part of a dyke and the resistance against erosion of its vegetational cover. The rate of loss of this unsaturated strength contribution mainly depends on the rate of infiltration of the water against the dyke. Unfortunately, in the interpretation of full-scale experiments on partly unsaturated dykes the effects of the capillary-suction induced strength is usually being neglected as well, thereby overestimating the strength of the saturated soil, assumed to dominate the overall failure mechanism. For peat dykes the shrinkage and cracking due to drought have been observed. In the near future this research topic may become recognised as important for determining the long-term effects of climate change. Much experimental experience will need to be gained before the top international research level on unsaturated soil mechanics will be even approached.

3 ANALYTICAL AND NUMERICAL MODELLING AND ANALYSES

Many analytical and numerical research topics can be defined, most of them related to the above-mentioned research topics. Some seemingly old-fashioned numerical research topics concern the

FIGURE 5
FAILURE OF THE PEAT DYKE ALONG THE GRAND CANAL NEAR EDENBERRY, IRELAND, IN 1989 DUE TO DROUGHT. (PIGOTT, HANRAHAN, SOMERS, 1992)

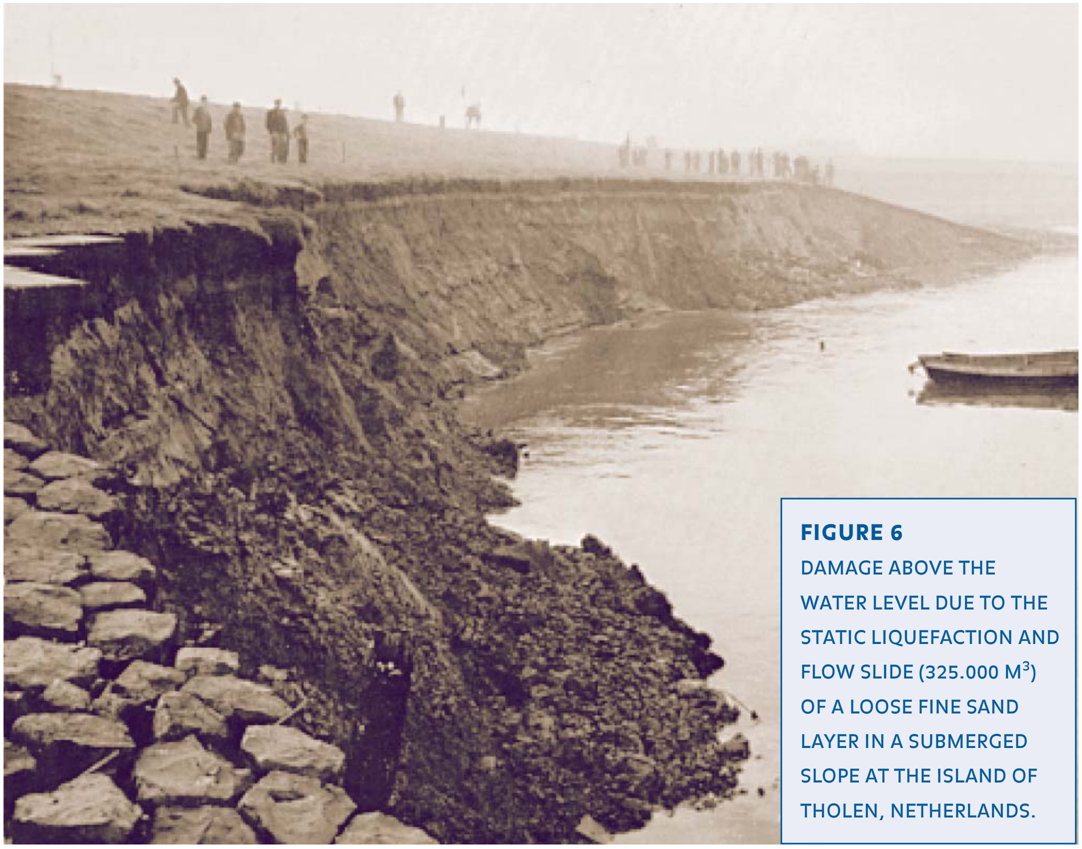


FIGURE 6
DAMAGE ABOVE THE WATER LEVEL DUE TO THE STATIC LIQUEFACTION AND FLOW SLIDE (325.000 M^3) OF A LOOSE FINE SAND LAYER IN A SUBMERGED SLOPE AT THE ISLAND OF THOLEN, NETHERLANDS.

simulation of geotechnical structures involving material models for monotonic loading, propagation of localization, instability and subsequent dynamic flow. However, despite the long-term efforts in the past only a limited level of success has been achieved, thus much more effort will be needed. For instance, for the simulation of continuing large possibly dynamic flow of continuously deforming soil various numerical techniques seem to be feasible, of which ALE and/or MPM may be found to be most suitable, depending on the problem at hand.

Apparently more respected research topics concern the geo-structural behaviour for transient loading, inducing pore-pressure generation, possibly involving inertial effects like earthquakes, leading to either shakedown or some form of failure.

Inverse and stochastic modelling is a rather recent numerical research topic, requiring extensive data collection for input and parallel-processing due to its computation-intensive character, which is already needed for 3-dimensional analyses anyway *(see figure 7)*. One promising application aims at the improvement of the control of tunnelling machines, so reducing the induced-settlement of the ground surface, although the tunnelling contractors are not famous for sharing the control of the steering of their tunnelling machines with the engineers of their clients.

For supporting the quality of simulations of dilative geomaterial behaviour, which is often an integral part of shear band initiation and propagation, accurate thin and long elements would be very useful. Here the continuation of specific combined analytical and numerical research is expected to become very worthwhile.

The simulation of the dynamic phenomena caused in the ground by a fast moving large load on the surface still requires further attention as well, where finite element and discrete element modelling seem to be competing for unavailable favours. For this problem, related to fast moving trains, the analytical solutions may be found to be most useful, despite their severe limitations, e.g. only allowing equivalent hysteretic-elastic material behaviour of one homogeneous layer.

For the simulation of the compaction by vibration and the effects of severe earthquake loading numerical methods seem feasible and inevitable.

The numerical modelling of deformation and strength of drying soil and the related flow of soil moisture and heat were initially developed for understanding the processes occurring due to the underground storage of nuclear waste. At present these processes are becoming more relevant both for predicting the effects of climate change and the phenomena involved in the underground storage of heat.

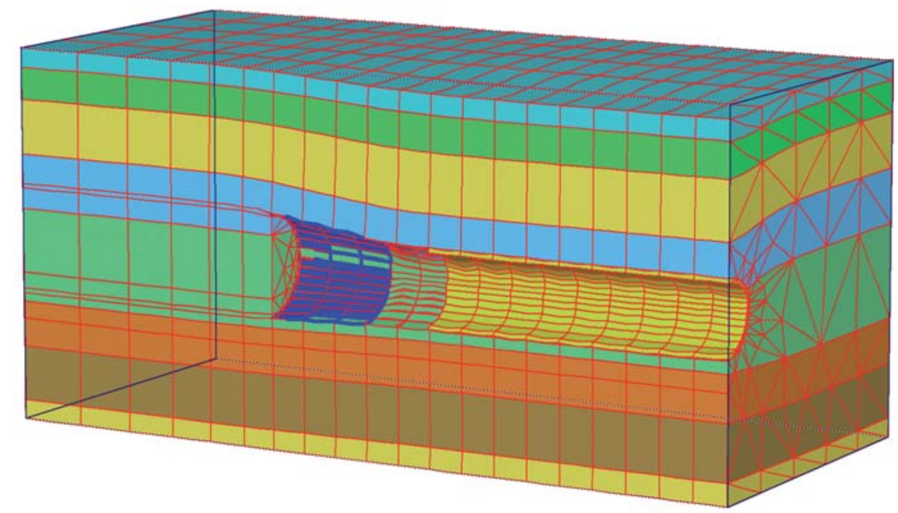


FIGURE 7
FINITE ELEMENT MODEL OF TUNNELLING PROCESS. DEFORMED MESH, (BROERE, BRINKGREVE, 2002).

Based on this approximate overview of research topics on soil mechanics it may be concluded that soil mechanics is by far not ready yet, as may be believed in some circles within Delft University. As I got older I started to recognise more and more relevant research topics in soil mechanics and nowadays I know that soil mechanics research has hardly started.

OPTIONS FOR OPTIMIZING SOIL MECHANICS

Potential options for optimizing the success of soil mechanics as a separate academic education and research field, worth of a Chair, concern the structuring of the organization of the teaching, research and application. Considering teaching the options should allow for at least a Master specialisation of with 300 teaching hours and various additional modules for specific designs and techniques. Concerning the research and/or application, the options should enable sharing specific research interest and/or application topics with soil mechanics.

CURRENT SITUATION WITHIN GEO-ENGINEERING

In the current situation soil mechanics is one small specialisation within the section of geo-engineering between the other specialisations of geo-environmental engineering, engineering geology, foundation engineering, tunnelling and groundwater engineering. This presumes that soil mechanics would always be too small to act as an individual section, which is contradicted by examples of successful organisational forms elsewhere.

Nevertheless, the current situation has as advantages that the research on flow of pore fluids (water and air) and heat and inverse and stochastic modelling may be shared with geo-environmental engineering and perhaps even interaction between biochemical and soil mechanical research may be possible. Furthermore intensive collaboration with engineering geology on at least various aspects of field and laboratory testing is important. Besides, in the longer term the research in engineering geology may produce further knowledge about geological processes for improving the spatial interpolation between the classical field data, so far involving mainly reliable vertical line data.

The applications involving the design and techniques for foundations, excavations, tunnelling and flow of fluids and heat can be shared section-wide and treated as joint efforts. However, concerning the teaching at the Master level insufficient teaching time (180 hrs) has been allowed, preventing the teaching of various essential soil mechanical topics. This is the major shortcoming of the current organisational form of geo-engineering, which in my view needs to be upgraded drastically for the Chair of soil mechanics ever becoming successful again. On the other hand, continuation of the current situation will lead to soil mechanics dissolving further, causing more faculty-wide loss of co-ordination, coherence and quality of teaching and research on soil mechanics topics by other individual civil engineering sections, taking up the more relevant aspects for them only.

CURRENT SITUATION WITHIN GEOTECHNOLOGY

In the current situation the geo-engineering section is part of the Department of Geotechnology together with the sections of Petroleum Engineering, Applied Geophysics and Applied Geology. The advantage of this organisational structure for soil mechanics within the section of geo-engineering may be that the organisational distance to the other civil engineering sections is equal, thus enabling equal forms of collaboration to all civil engineering sections rather then tying soil mechanics to only one of the other four or five civil engineering Departments, while temporizing collaboration with the others. The advantages of the current situation for soil mechanics concern also aspects of the experimental research on Petroleum Engineering, in particular the failure of rock by shearing and fracture mechanisms and possibly the unsaturated flow of water, air and heat. In addition, geophysical research on the shallow subsurface may in the longer term improve the insight into the heterogeneity of the ground, giving soil mechanics another tool for field investigation.
However, the major disadvantage is that most teaching and research topics concern different non-civil engineering application fields, which may alienate civil engineering students from taking soil mechanics for their Master study.

POTENTIAL OPTION WITH HYDRAULIC ENGINEERING AND FLUID MECHANICS

The option of combining the teaching and research on soil mechanics with the sections of Hydraulic Engineering and Fluid Mechanics would be similar to the situation I found in 2002. However, here faculty-wide collaboration in teaching and research and achieving the full Master teaching programme are assumed to be prerequisites. Advantages would be collaborative research on dykes, hydraulic structures, dredging etc. and on stochastic and inverse analyses. Also shared research with the section of Fluid Mechanics would be facilitated more easily, e.g. on the interaction at the interface of a submerged slope of dense sand and free water, involving the phenomenon of breaching and density current.

POTENTIAL OPTION WITH CONSTRUCTION

Another potential option for soil mechanics would be to join the Department of Construction. An important advantage would be that the teaching and research on many aspects of mechanics and dynamics, material behaviour, failure mechanisms and numerical geomechanics would overlap significantly. After all, soil mechanics shares most of its background with structural mechanics and due to the continuing growth of shared computer applications also research products in the form of software are often shared, with only partly complementary applications for soil mechanics. The differences concern mainly the multi-phase aspects of soil mechanics, but even this difference is decreasing as the hardening process of concrete is also being considered as a multi-phase process with even an additional chemical component. Particularly fruitful collaboration can be foreseen with the section of computational mechanics on various topics and concerning both teaching and research. However, for soil mechanics a governing disadvantage could be that the Master teaching programme (300 hrs) could not be fitted within the Departmental teaching programme. Furthermore, the faculty-wide collaborative teaching and research should not become hampered in any way. This would require detailed discussions on sharing the teaching topics so maximizing the teaching efficiency while realizing the envisaged full width of soil mechanics teaching and agreement on sharing teaching and research with other Departments of the Faculty.

POTENTIAL OPTION WITH ROAD- AND RAILWAY ENGINEERING

Another potential option would be to form a new relatively small Department together with the current section of Road- and Railway Engineering. This might also enable the reorganization of the section of geo-engineering, e.g. allowing for further improvement of the teaching programme of geo-environmental engineering.
The advantages for soil mechanics (and dynamics) would be that the research on embankments, excavations and tunnels for transport could be shared and the interaction between on one hand the road and railway and on the other the ground could be tackled together more easily. In this option the envisaged Master teaching programme of soil mechanics might be realised rather easily. Again a governing condition would be that the faculty-wide collaborative teaching and research should remain possible.

CONCLUSIONS

In this note the case of the continuation of soil mechanics as a Chair topic has been made. Looking at its research prospects in relation to the large societal needs, it appears to me that soil mechanics is awaiting a great future!

It is noted that sofar the suitability of the current organisational structure of soil mechanics in the section of geo-engineering within the Department of Geotechnology has not been evaluated as yet. Hopefully my successor will find an opportunity to review, evaluate and optimize the situation, for which I believe negotiations for a better position with all sections and departments of the faculty will be needed, such that more civil engineering students are attracted and the envisaged Master teaching programme can be realized, so enthusing both more civil engineering Master students and future PhDs for soil mechanics, who will be able to address the large range of research questions with large relevance for society, thus justifying the Chair. ■

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