Automatic calculation of phased building processes including consolidation periods

Calcul automatique de processus de construction phasée comprenant les périodes de consolidation

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ABSTRACT: This paper deals with the aspects of building processes. The focus is at the automatic calculation of time-schedules. The time schedule is nowadays a very important factor when realizing projects. An important advantage of the method described here, is that the automated process can easily be used to investigate the effect of construction variants, such as the application of drainage systems or geotextiles.

1 INTRODUCTION

In regions with soft soils, embankments form an important part of the daily work of geotechnical engineers. For embankments on soft soil many factors play a role. During the raising of the embankment the undrained short term behavior is important. During the raising of the embankment the pore pressures may increase which influences the overall stability of the embankment. Therefore in many cases it is necessary to pause the raising of the embankment to decrease the pore pressures (consolidate). When the pore pressures have decreased and the stability has increased it is possible to continue the raising of the embankment.

The process of raising an embankment may take many steps of applying some soil and consolidation, especially in case of a high embankment on very soft soil. The estimation of suitable building stages and consolidation times can be very time consuming for the geotechnical engineer and an automatic procedure, or "expert system", is requested. Such an expert system will give a good impression of a suitable time schedule of the building process.

2 DESCRIPTION OF THE BUILDING PROCESS

In general, when relatively high embankments are to be build, it is raised in stages; each stage consists of the of the application of for instance half a meter of soil at a time. The thickness of each layer depends mostly on the way a layer is applied. Depending on the scale of project and the availability of machinery and human resources, it can take several days before a new layer can be applied. New layers will be applied as long as safety is guaranteed. If the safety of the embankment becomes too low, the building process stops. In time, the safety of the embankment will increase due to consolidation. When the safety of the embankment allows for application of additional layers of soil, the building process is continued. It is possible that the completion of the embankment may take several relatively short periods of building with long breaks in between. Schematically, the building process is given in Figure 2, it is assumed that the actual application of a layer is performed very rapidly. During the (short) time between the application of two layers some consolidation can take place. In practice this will give nearly the same results as when the actual application is applied smoothly in time using the "average" raising rate.

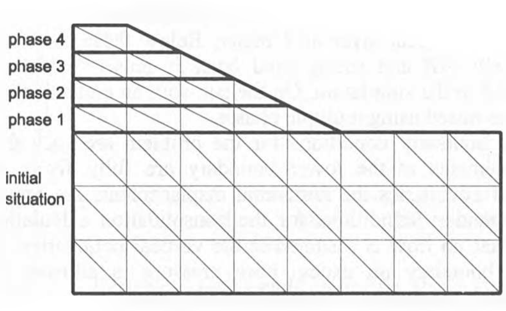

Figure 1. Example of mesh with building phases.

3 SIMULATION OF THE BUILDING PROCESS

The simulation of the building process consists of different types of calculations. For the application of a layer, a plastic calculation is performed using undrained behavior for the sub-soil which usually consists of soft soils with low permeabilities. Rapid application of load will give undrained behavior in the sub-soil, volume changes are prevented as the water will have no time to flow. This undrained behavior will result in the build up of excess pore pressures.

At the start of the calculation, the weight of the additional elements is activated. This will usually result in a large unbalance. This unbalanced load will automatically be applied in several steps, such that when the initial unbalanced load is fully applied, this will result in an equilibrium state.

After the application of a layer a short consolidation period is allowed for. During this period the excess pore pressures will give some flow of water. In practice, the short consolidation period will not reduce the excess pore pressures very much.

It is possible that the plastic "Staged Construction" calculation does not reach equilibrium for the final state; the embankment may fail. In that case, an additional consolidation period has to be inserted before the current stage. Depending on the safety one wants to ensure, it might even be necessary to insert the extra consolidation period before the previous stage.

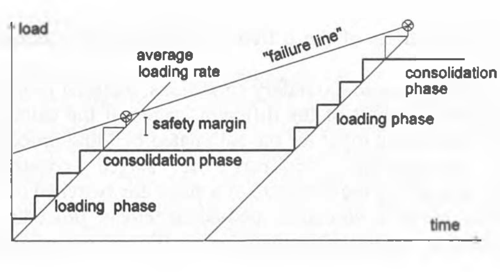

Figure 2. Simulation of building process; subsequent loading and short consolidation until the failure line is approached, then a long consolidation period is required.

4 SAFETY

A rigorous way to determine the safety of the construction would be to include strength reduction calculations before and after each building phase, and depending on the result of the strength reduction calculation decide to start the building phase or insert a long consolidation period. Instead of the above approach, we use a different approach. Our approach is based on the possibility to apply extra load. During a building phase, the calculation might fail, in the sense that a failure mechanism can arise during the building phase. One can determine the height at which failure takes place.

The safety factor is defined as the height that can be applied divided by the height to be applied. In other words, when one wants to apply a building phase of one meter, and a safety factor of 1.25 is demanded, one should be able to apply at least 1.25 m before the one meter building phase can be applied safely. When a staged construction calculation detects failure, it is possible to determine the height at which this occurs. Based on the height that is found, one can find a "safe" application height and one should find the last building phase, not exceeding the safe height. After a safe building phase an additional consolidation period should be inserted. This extra consolidation period will be much longer than the period between two stages, weeks or months compared to days. This long consolidation period will allow for dissipation of excess pore pressures and at the same time the effective stresses will increase resulting in higher strength of the sub-soil. After such a long consolidation period one can start the building process again with subsequent staged construction calculations and (short) consolidation periods until failure is detected again. At this time one has to determine a safe height again and insert another long consolidation period. This process is continued until the embankment is fully applied.

The simulation process is depicted in Figure 3. The scheme uses different processes or programs. Two calculation programs, plastic and consolidation programs, an "expert" system and, as usual, input and output programs. The links between the programs are shown in Figure 4.

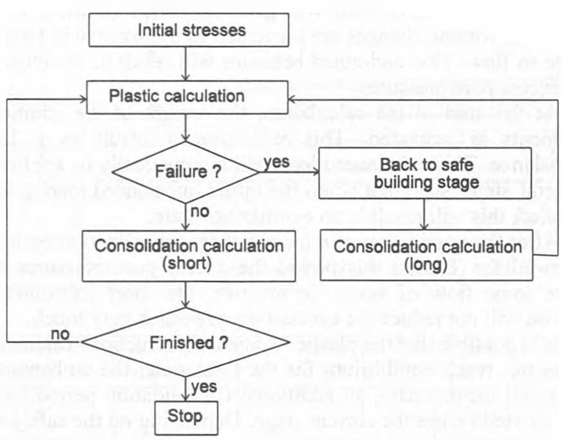

Figure 3. Schedule for the simulation.

Some of the options of the different programs are summarized below:

- Input: Prepare mesh, boundary conditions, material properties. Also used for input of the different stages of the calculation and the additional input for the automated building process.
- Plastic calculation: Performs the staged construction calculation where the elements of a stage are switched on. The program includes so-called load-advancement procedures to get a smooth load-displacement curve. When steps need many iterations to reach equilibrium, automatically smaller steps are taken and vice versa (Van Langen & Vermeer, 1990). To be able to find limit states an arc-length procedure is included. Failure of the soil body is assumed when the load decreases in two subsequent steps. For the automated loading process as described here, failure is also assumed when the stiffness has reduced very much and the load is not reaching the final load for the current stage.
- Consolidation calculation: This program includes elasto-plastic consolidation (Song, 1990). As in the plastic calculation, the size of the time steps is automatically changed when the number of iterations per step is very small or very large.
- Expert program: This program controls the actions to be taken. Initially the first plastic staged construction calculation is started. After each calculation, the results (finished, failure etc.) are stored and depending on the result of the calculation the next calculation is prepared. This next calculation phase can be either a plastic or a consolidation calculation.
- Output program: This program can be used to view output of different steps of the calculation. This can be in the form of displacements or stresses. Also, it is possible to review the total simulation process.

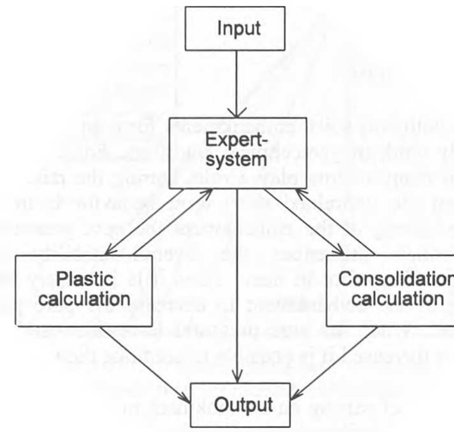

Figure 4. Relations between programs.

5 NECESSARY INPUT

The automatic procedure requires limited additional user input. As in all other calculations, one has to provide a finite element mesh, boundary conditions and material properties. The mesh should be designed such that each building stage consists of a number of elements because later the building phases are simulated by "switching on" all the elements for the particular phase.

Additional input of the procedure consists of which elements are to be switched on in every building phase, the (short) consolidation times between the stages, the safety margin and the size of the (long) consolidation period when failure occurs.

6 EXAMPLE

In Figure 5, the mesh is given for the calculation of an embankment on soft soil using the automatic loading procedure.

The sub-soil consists of two soil layers, a clay layer of 6 meter underlying a peat layer of 4 meter. Below these two layers, a relatively stiff and strong sand layer is present which is not included in the simulation. On the sub-soil, an embankment of 6 meter is raised using multiple phases.

The boundary conditions for the problem are such that the displacements at the lower boundary are fully fixed, at the vertical boundaries the horizontal displacements are prevented. The boundary conditions for the consolidation calculation are such that no flow is assumed at the vertical boundaries. At the lower boundary no excess pore pressure is allowed as the problem is situated on a permeable sand layer.

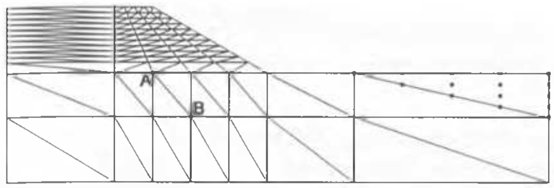

Figure 5. Example mesh. The embankment consists of one layer of 1 m and 10 layers of 0.5 m to reach an ultimate height of 6 m.

The material parameters that are used are given in Table 1. The lower soil layer is a clay layer, the second layer, initially at the soil surface, is the peat layer. The embankment consists of sand.

Table 1. Material properties

	Clay	Peat	Sand	
Thickness	6	4	6	m
Soil weight (wet)	16	11	20	kN/m^3
Hor. permeability	1.10^{-9}	2.10^{-8}	5.10^{-6}	m/s
Vert. permeability	1.10^{-9}	1.10^{-8}	5.10^{-6}	m/s
Shear modulus	700	200	5000	kN/m^2
Poisson's ratio	0.333	0.333	0.3	-
Cohesion	3	5	1	kN/m^2
Friction angle	20	25	30	°
Dilation angle	0	0	0	°

The first building phase consists of an additional layer of sand of 1 meter, after this layer a layer thickness of 0.5 meter is used. Between the application of each layer a (short) consolidation period of 1 day is used. The margin of safety that was applied was 20 percent, meaning that the layers with a thickness of 0.5 meter can be applied safely when it is possible to add 0.7 meter without failure occurring. When failure occurs, additional (long) consolidation periods of 28 days are used.

In Figure 6, the results of the calculation are shown as a time-height diagram. The bold line in the figure gives the resulting building scheme according to the entered safety factor. The dead ends result from failed tries. Either the building stage could not be fully applied or the safety of the embankment was found to be too low and an additional (long) consolidation period had to be applied.

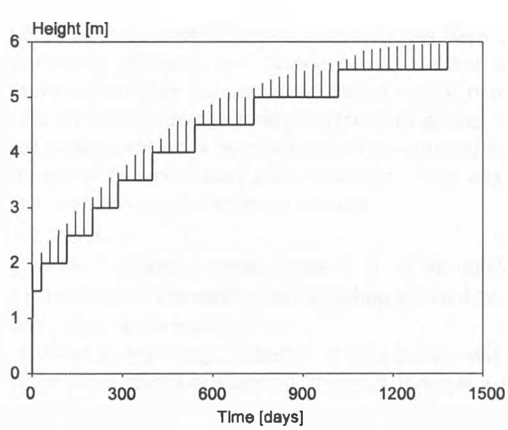

Figure 6. Resulting time-height schedule (bold line); the dead ends follow from the unsafe tries.

In Figure 7, the displacement of point A (in Figure 5) is given. Again, the bold line gives the resulting height-displacement curve. The other lines show excessive deformations indicating failure of the structure. In that case, a previous, safe, stage is found and an additional long consolidation period is inserted.

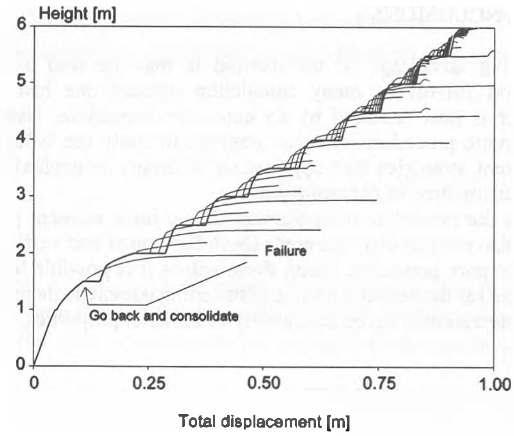

Figure 7. Total displacement of point A of Figure 5. The bold line is the final result; the dead ends result from unsafe tries.

In Figure 8, the excess pore pressure of point B is shown. It is clear from this figure that in the unsafe tries, the excess pore pressure did not reduce enough to allow for an additional building stage. As can be seen from the figure, failure seems to be dominated by the excess pore pressure, which is closely related to the effective stresses and therefore to the strength of the soil. In the unsafe tries, the strength was not enough to be able to add an additional building stage.

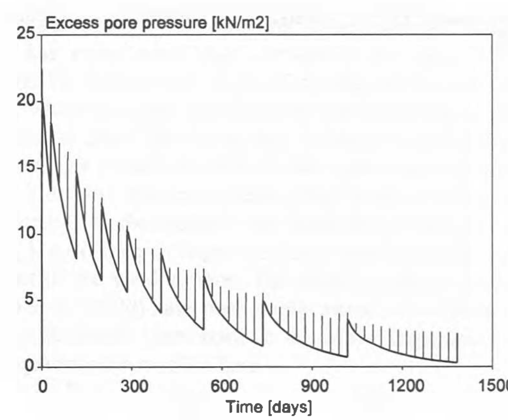

Figure 8. Excess pore pressure in point B of Figure 5. The bold line is the final result; the dead ends result from unsafe tries.

7 PERSPECTIVE

The automated calculation procedure can be used to investigate quickly the effects of alternatives. One can easily include for instance geotextiles, repeat the calculations and compare the results of the calculations with respect to for instance displacements or building time. One can also include the effects of a drainage system. To this end, one can either introduce drainage elements or additional (zero excess pore pressure) boundaries inside the mesh. Also, one can use equivalent (vertical) permeabilities in the sub-soil to simulate a vertical drainage system.

Finally, one can use the results of the simulation to derive criteria and take decisions based on these criteria during the actual building of an embankment. One can for instance use the results of the excess pore pressures in different points and compare them with measurements in stand pipes and adapt the building schedule.

8 CONCLUSIONS

The big advantage of the method is that the trial and error method (involving many calculation phases) one had to use earlier is now replaced by an automatic procedure. Using this automatic procedure it is also possible to study the influence of different strategies like application of drains or geotextiles, on the raising time of the embankment.

As the procedure is implemented in a finite element program one also obtains displacements (both horizontal and vertical) and excess pore pressures. Using these values it is possible to derive criteria for the actual building of the embankment as there always are uncertainties in the availability of material properties.

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REFERENCES

CUR publication 178 1995. *Achtergronden bij de numerieke modellering van geotechnische constructies*, part 1, Stichting CUR, Gouda The Netherlands (in Dutch).

Langen, H. van & Vermeer, P.A. 1990. Automatic step size correction for non-associated plasticity problems. *Int. J. Num. Meth. Eng.* 29: 579-598.

Song, E.X. 1990. *Elasto-plastic consolidation under steady and cyclic loads*. Ph. D. Thesis, Delft University of Technology, Delft..