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Geotechnics in Hydraulic Engineering

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SYNOPSIS Hydraulic engineering is an important part of civil engineering in low lying coastal areas, where the water in the rivers and seas has a great influence on the design of all structures. This is especially so for structures built in the soil, because the soil in such areas usually is very soft, and the groundwater level is close to the ground surface. For the construction of many structures the behaviour of the soil and the water have to be taken into account, and thus there is a large interaction of geotechnical engineering and hydraulic engineering. In modern civil engineering it is no longer so that one branch of engineering simply provides the boundary conditions for another branch of engineering: their interaction should be considered in an integrated analysis. Geotechnics is an essential part of hydraulic engineering.

1 INTRODUCTION

In the beginning of the millenium that is now approaching its end the people living in the delta formed by the lower branches of the rivers Rhine and Meuse, the area that is now called the Netherlands, began to protect their lands from flooding by constructing dikes along the rivers. Figure 1 illustrates that these dikes indeed protect the houses from being under water.

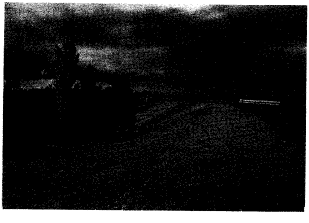

Figure 1: A dike in the Netherlands.

By building dikes an irreversible process was started, of continuous raising of the level of these dikes to offset the gradual subsidence of the soft soils, which were no longer raised naturally by the fertile silts added in each flood (Israel, 1995). The history of the Netherlands records many periods of floods and subsequent construction or reinforcement of dikes and embankments, and sometimes the rising of bridge abutments or of entire sluices. This is a process that will continue forever, sometimes as part of a normal maintenance scheme, but more often as a result of recent floods.

2 GEOTECHNICS IN THE NETHERLANDS

In areas with soft soils and a high groundwater table, such as the Netherlands, there are two major difficulties in performing large scale civil engineering works. The first difficulty is that in soft soils it is difficult to ensure stability and to restrain deformations and settlements. The second difficulty is that the high groundwater table may lead to problems of leakage and uplift. In this paper these difficulties, and some of the possible solutions, are illustrated, emphasizing the construction of infrastructure: dikes, highways, railways, waterways, and their crossings. Particular attention is paid to the necessary or desirable further developments of geotechnics to satisfy the needs of the future.

3 DIKES

The rivers of the world carry variable amounts of water. For the Netherlands the main river is the Rhine, which transports water from the mountains in Switzerland and Southern Germany and rain water over a large part of Germany, Switzerland, France, Belgium, Luxemburg and the Netherlands to the sea. The minimum discharge is sufficient to maintain a water level enabling shipping traffic throughout the year, but the maximum discharge is so high that the course of the river has to be controlled by dikes. A schematic

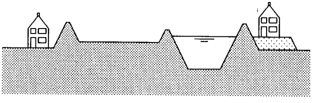

Figure 2: River with dikes.

cross section of the river is shown, not to scale, in Figure 2. In summer, when the water level is relatively low, the river is flowing between the *summer dikes*. In winter, when the discharge of the river may be very large, the river bed widens over the flood plains, and extends to the *winter dikes*.

3.1 Criteria

The main purpose of the dikes is clearly the protection of the land against flooding, and for this purpose they have to be high enough and strong enough to withstand the maximum expected flood. Traditionally the maximum flood level was determined by taking the maximum flood from the past, and perhaps adding some additional height, for safety reasons. This was satisfactory, until a flood level occurred that surpassed all previous levels. After the experience with floods in this century it has been decided to base the design criteria on a more scientific basis. In the Netherlands this has resulted in the establishment of probability criteria in the national law. For dikes along the sea it has been decided that they should be able to withstand conditions occurring once every 10000 years. For river dikes, for which there is a longer time available to warn the population, and the disaster damage may be somewhat smaller, at least in human lives, the design criteria are based on the water levels for a flood occurring every 1250 years.

Application of these criteria to the existing dikes has lead to the conclusion that many of the dikes should be raised, and strengthened. Before 1993, when memory of high river levels had faded from peoples memory, local opposition to the plans made for raising the dike levels was great, from people living close to the dikes, whose houses had to be removed, and especially from people who wished to protect the unique vegetation on and near the existing slopes, or who wished to preserve their view of the river, and lived on higher ground themselves. After the high water levels in the winters of 1993 and 1995 this opposition practically vanished, and many projects of dike reconstruction have been executed. It can be expected that the new houses built near the new dikes and the new vegetation that will grow in a couple of years will be considered just as valuable and indispensable as the old ones. If it appears in the course of the next century that the dikes are again too low, and this is very well possible, because of climate changes and developments in land use, it will probably again be difficult to obtain sufficient public support for further reconstruction of the dike system.

3.2 Strength of a dike

The usual way to evaluate the strength of a dike is by performing a stability analysis, on the basis of a consideration of the safety of circular slip surfaces, see Figure 3. The analysis consists of calculating the safety factor for a great number of possible circular slip surfaces, and then determining the minimum safety factor. The safety factor is defined as the ratio of the strength of the structure, i.e. the moment of the shear stresses along the slip surface about the center of the circle, and the load, i.e. the moment of the weight of the sliding wedge about the center of the circle. This is in agreement with the usual definition of a safety factor of a structure as the ratio of its strength to the load.

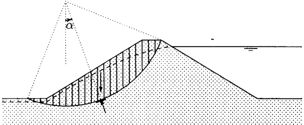

Figure 3: Slip circle analysis.

The calculation is usually performed by subdividing the soil wedge in a large number of vertical slices. The formula is

$$F = \frac{\sum(c + \sigma_n' \tan\phi)/\cos\alpha}{\sum \gamma h \sin\alpha} \tag{1}$$

The numerator of this fraction expresses the moment of the maximum possible shear stresses, which depends upon the cohesion c and the angle of internal friction ϕ. The denominator is the moment of the weight of all slices, depending upon the local weight γ and the height h of the slice. The quantity σ_n' is the normal stress, acting upon the slip surface. This has to be calculated from some additional condition, for instance vertical equilibrium of all slices. A well known and effective method has been proposed by Bishop (1955). This method is widely used, with good results.

For a proper understanding of the methid it is helpful to note that the factor $\sin\alpha$ in the denominator of formula (1) represents the excentricity of the force, which determines the moment of the weight of a slice about the center of the circle. For points to the left of the center this factor is negative, indicating that the material on the left side of the center reduces the moment of the load.

The analysis involves a number of simplifying assumptions, for instance regarding the stress distribution in the interior of the sliding wedge, and regarding the pore water pressure distribution, and is therefore open to further improvement. Actually, compared to the state of the art of structural computations in other fields, and even compared to the sophisticated methods of analysis available in soil mechanics, a stability analysis using slip circles is a rather primitive tool, and it can be expected that more refined methods will be developed.

Developments that can be expected are the further incorporation of modern numerical methods in the stability analysis of slopes. These methods are often used for complicated situations, but the simpler slip circle remains very popular, because it enables to execute large numbers of computations, for various geometries and soil properties.

3.3 Statistical soil properties

The further development of methods of analysis of the stability of slopes is complicated by the circumstance that a large body of positive experience has been built up in the twentieth century, even when using relatively low factors of safety. In the Netherlands the factor of safety required for new dikes, under normal conditions, is 1.3, and the factor of safety required for existing dikes is 1.2. Although these relatively low values – in the construction industry significantly larger factors are used – may have been established to balance certain conservative assumptions in the method of analysis, such as the determination of the shear strength in laboratory tests, and the improvement of soil properties during the long history of the dikes, it will not be easy to develop a new method that can replace the existing successful method.

One of the possible improvements seems to be the characterization of the soil properties by statistical values rather than the deterministic values used now. A difficulty in this area of further development is that geotechnical engineers are used to interpret a single low value of a soil property among a large number of higher values from a soil investigation campaign as an indication of a thin soft layer. If this is then incorporated into a classical analysis the safety factor remains dominated by the high values in the majority of the layers. In a statistical interpretation, of a homogeneous layer with statistically varying soil properties, the strength parameter would probably be reduced much more, which would lead to considerably smaller values of the safety factor. Dikes that have shown the sufficiency of their strength might then well have safety factors smaller than 1, which cannot be true.

To illustrate this point let it be assumed that the soil investigation for a slope stability analysis has been performed by taking ten samples, and that all samples have the same strength c_0, except for one sample, which has half that strength, $\frac{1}{2}c_0$. The classical interpretation of this data is that the soil contains a single layer, of about one-tenth of the height, of smaller strength, at the depth where the smaller strength was encountered, see Figure 4. This leads to a safety factor that is about 5 % smaller than the original value: 1.23 instead of 1.30. A possible statistical interpretation would be that the average strength of the soil is 0.95 c_0, and that the standard deviation is 0.15 c_0. The usual statistical methods then suggest that a value of 0.65 c_0 should be used to ensure a 95 % certainty that the result is safe. This would lead to a safety factor 35 % smaller than the original value, and if the original safety factor was 1.3 the final value will be 0.85, which is indeed smaller than 1. It appears that a statistical interpretation of soil testing results can easily lead to very small safety factors, much smaller than the classical results, which are already very low. The explanation for this apparent contradiction is that soil strength is not a statistically homogeneous variable, and that in the stability analysis it is not the smallest possible value of the strength that determines failure, but really the average strength along the sliding surface. This is immediately clear from the basic formula (1), in which the strength of all elements is added. It appears that statistical methods that work fine for systems with parallel failure modes, do not work so well for systems in which failure depends upon many elements in series that should all be failing.

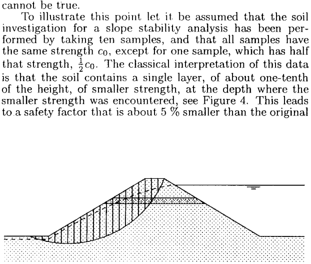

Figure 4: Non-homogeneous dike.

Even when using a more sophisticated statistical approach, on the basis of the notion that the failure of the slope requires the simultaneous failure of a large number of elements, some difficulties arise. In such an analysis the standard deviation of the average strength of the entire chain of elements will be a factor $\sqrt{n}$ smaller than the standard deviation of the strength of an individual element, with n being the number of elements in the series (Kreyszig, 1970). If $n = 10$ this means that the standard deviation is a factor 3.16 smaller. In the example given above this would mean that the standard deviation would be about 0.05, and the safety factor would be 1.10, which might still be considered sufficient. The difficulty is, however, that there does not seem to be a valid reason to set $n = 10$, or perhaps $n = 100$, or even taking n equal to the number of grains along the failure surface. The conclusion can be that much research is to be done in the next millenium before the classical deterministic method of analysis can be improved.

3.4 Emergency measures

It may be instructive to point out that the slip circle analysis methodology can be used to justify some of the techniques that are used in practice to save a dike in critical conditions, and that must be based upon experience and intuitive notions of local authorities and experts. In the winter of 1995 extreme rainfall over a large area in the drainage basins of the rivers Rhine and Meuse caused exceptional high water levels in these rivers. The water levels were considered so critical for the stability of the dikes that hundreds of thousands of people were evacuated from the most critical areas. Stability analysis of the dikes indicated that the safety factors were close to 1, and might obtain values below 1. Actually, in many locations water levels came very close to the level of the crest of the dikes, and in several locations cracks were observed to occur in the crest, indicating the possible beginning of failure, with water levels still rising. Scientific interest might have been served by doing nothing but observing the behaviour of the dikes, to compare it with the predicted failures. But human nature prevailed, and the authorities and the population tried to save their dikes.

One of the possible measures is to apply a load, by placing sand bags, or just large quantities of sand, near the lower part of the downstream slope, see Figure 5. The positive effect of this procedure can be verified from the basic formula (1). The weight of the slices on the downstream side, where $\alpha < 0$, is increased, so that the value of the denominator is reduced, which increases the value of the safety factor. The effective stress σ'_n is probably also increased, so that the numerator may be increased. This effect is not so certain, as most of the additional load may simply result in extra pore water pressures. The main effect is the reduction of the moment of the load.

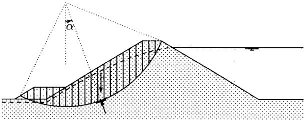

Figure 5: Sand bags on the downstream slope.

For the same reason local authorities often prohibit traffic by heavy vehicles on the crest of the dike, when the dike is in danger. Such a load would increase the moment of the load, and thus reduce the safety factor. It can also be seen from the formula (1) that it is also not advisable to put heavy sand bags on the crest of the dike, at least not if the water has not yet reached the level of the crest. When the water level is so high that water threatens to overflow the dike, sand bags on the crest may help to avert this extreme danger, of course.

Another emergency measure to prevent failure of a dike is to cover the upstream slope by an impermeable flexible membrane, see Figure 6. The purpose of the membrane is to prevent water to enter the interior of the dike body. This

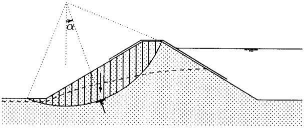

Figure 6: Membrane on the upstream slope.

retards the increase of the pore water pressures in the soil, which is a favourable effect. On the one hand the weight of the soil, and hence the driving moment, is reduced. On the other hand the reduction of the effective stresses along the slip surface is also retarded. Thus the denominator of the safety factor (1) is reduced and the numerator is increased, so that the safety factor is larger than in the case of a rapid inflow of water into the interior of the dike. Of course the membranes should cover a sufficiently large area, and the individual sheets should be well connected. Also, they only retard the pore pressure increase; if the flood continues long enough the groundwater level will rise eventually, and the danger may be as large as it was without the membrane. The method has worked well, however, in several critical locations in the Netherlands in 1995. The critical high water level lasted only for a few days, and during that period water inflow was indeed reduced sufficiently to save the dikes.

4 HIGHWAYS AND RAILWAYS

When a highway or a railway line has to be built through an area consisting of very soft soils, one of the main problems is to prevent large future settlements of the soil surface. Often this can only be achieved by using an extensive form of soil improvement. For this purpose geotechnical engineering presents several effective techniques. A typical hydraulic technique is to remove much of the very soft material by first dredging a canal following the path of the future highway, a cunett, and then filling in this cunett by a better quality soil, for instance sand, see Figure 7, which shows the completed road. This method requires high capacity dredging equipment, and it also requires the availability of large quantities of sand, and some place to store the dredged soft material. Such projects have been executed in the Netherlands in combination with development projects of industrial or recreational areas. A new lake may be created in the location of the sand pit, and a new park may be created on the site where the soft soil is dumped.

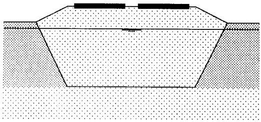

Figure 7: Highway built in cunett.

5 IMMERSED TUNNELS

In the Netherlands several tunnels under rivers or canals have been constructed using a hydraulic method, the *immersion method.* In this method the tunnel is built up of a number of separate elements, of say 100 m length, which are constructed in a building dock, floated to the location of the tunnel, submerged in a channel dredged in the river, and finally covered with sand. In the Netherlands the method was first used just before the second world war to construct the first tunnel under the river Meuse in the city of Rotterdam (Vreugdenhil, 1942). For the construction of an underground railway in the city of Rotterdam this method has also been used, in the early sixties (Stiksma, 1993). Even in the center of the city where one of the main streets was temporarily converted into a channel for the transportation of the tunnel elements and the construction of the final tunnel, see Figure 8. One of the advantages of this hydraulic method is that the water table is never lowered, so that the effective stresses in the vicinity of the project are not affected at all, and deformations are prevented. In a time when the main alternatives were open excavation methods, using lowering of the ground water table, the immersion method was a popular method. The main disadvantage is, of course, the disruption of local traffic, commerce and social life in the vicinity of the construction site. With the modern development of tunnel boring methods for soft soils, using shield tunneling methods, hydraulic methods will probably no more be used in built up areas. The next century will see many shield tunnels be completed in the Netherlands. The first project has been completed in 1998, and several tunnels are being constructed at the end of the millenium.

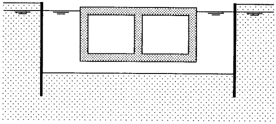

Figure 8: Floating tunnel element in cunett.

6 EXCAVATIONS

One of the main difficulties in civil engineering in areas with soft soil and a high groundwater table is that an excavation can only be made taking great care for the stability of the soil at all stages of the work. In many projects an excavation is an essential element, for instance for the construction of a basement or as part of an underpass or a tunnel, or to build a foundation. The problem is illustrated in Figure 9, which shows an excavation in a sandy soil, with sheet pile walls down to a layer of very low permeability, say a clay layer, assuming that there is such a layer. The situation drawn in the figure is probably not stable, because the water pressure below the impermeable layer is probably greater than the total stress in the excavation due to the weight of the sand and the clay. In geotechnical terms a critical situation occurs because the total stress σ is greater than the pore pressure p, and the effective stress $\sigma' = \sigma - p$ would be negative, which is impossible because the particles of a soft soil can

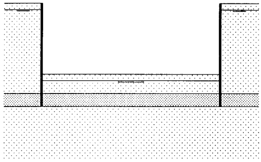

Figure 9: Excavation.

not transmit tension. The situation can be stabilized by making the excavation less deep, but very often that is not a feasible option, because the project requires an excavation to a certain depth, for instance to accomodate a certain number of floors for an underground parking.

Another solution would be to lower the groundwater pressures below the impermeable layer by pumping wells. This is often not allowed, however. In built-up areas lowering the groundwater table may lead to settlements of surrounding soil and structures, and in agricultural or remote areas lowering the groundwater table may be harmful to the crops or the natural vegetation. In densely populated countries such as the Netherlands lowering the groundwater table therefore usually is not a realistic option, at least not for prolonged times.

A better solution is to apply a thick floor of heavy concrete, see Figure 10. As concrete is about a factor 2.5 times as heavy as water it follows that every meter of water pressure can be balanced by 0.4 meter of concrete, which may lead to very thick layers of concrete. It may be noted that the very thick layer of concrete may lead to various technical difficulties, such as the continuity with the vertical wall, but there is little risk of large settlements, as one might expect for such a thick and heavy layer. The reason is that the concrete is merely a replacement of an original system of soil layers, so that the soil below the concrete is unloaded and reloaded below its preconsolidation stress. Soils are known to be very stiff in those circumstances. Usually the effective stress level below the concrete floor remains well below its original value, and the soil should behave stiff, as long as the effective stress remains positive, i.e. compressive, of course.

Figure 10: Concrete floor.

As an alternative a relatively thin floor slab may be used, together with a large number of tension piles to withstand the uplift forces from the groundwater, see Figure 11. The tension piles derive their capacity to the friction with the surrounding soil. This friction may be reduced by the reduction of the effective stress due to the excavation. It can be increased by using a dense mesh of driven massive piles, which probably will increase the lateral effective stresses. Actually, the determination of the maximum allowable tension force of the piles should be the subject of an extensive site investigation and careful analysis. Some pile tests may be very helpful in this process. It would be disastrous if the piles can not carry the actual load. Unlike piles in compression, which usually develop a greater capacity when deforming, tension piles loose some of their capacity upon significant deformation.

During all stages of construction the structure must be stable, of course, and this can best be accomplished by executing the excavation, the driving of the piles, and the construction of the concrete floor slab "in the wet". In Figures 10 and 11 no impermeable soil layer has been assumed, as the concrete slab can also act as an impermeable barrier, and thus these techniques can also be used in the absence of an impermeable soil layer. It should be noted that the water table above the concrete should be lowered only after all the construction work has been completed. The excavation, the driving of the piles and the construction of the concrete slab must all be performed under water. The construction of an impermeable slab of concrete under water deserves particular attention, taking care that the fluid concrete is poured homogeneously and continuously. All this requires special equipment and special techniques, but all these have been developed in the final decades of the twentieth century. In the Netherlands many tunnel entrances, and underpasses below highways, railways and waterways, in the form of aqueducts, have been constructed in this way. An example is shown in Figure 12, the entrance section of the underpass of an aqueduct near Gouda, on a very quiet moment, early on a Sunday morning. The walls of the underpass may consist of steel sheet piles, or of concrete walls, constructed from the original surface as diaphragm walls.

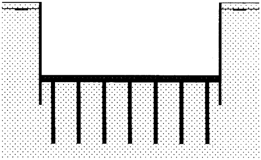

Figure 11: Tension piles.

For the future one may foresee a further development of creating impermeable walls and layers in the ground, by injecting cement or various chemical products, or by mixing the soil in place with hardening materials on the basis of cement or lime. These methods have been used successfully to reduce the permeability and to increase the strength of

Figure 12: Aqueduct near Gouda.

the soil. The artificial creation of a practically impermeable layer in non-homogeneous soil layers requires some further engineering development, however.

7 MEMBRANES IN HYDRAULIC ENGINEERING

An interesting method to construct a road below ground surface is illustrated in Figure 13. This is perhaps the ultimate application of hydraulic equipment in construction on dry land (d'Angremond, 1984). Let it be assumed that a road surface must be constructed at a depth of about 10 m below ground surface. The process starts by the hydraulic excavation, using dredging equipment, of a canal of about 20 m deep, about twice the final depth of the final road. In this canal an impermeable membrane of synthetic material is laid over the entire bottom of the canal, as a simulation of an impermeable bottom layer. The canal above the membrane is then back filled with sand, using the same dredging equipment as used for the excavation, filling the canal in the center to a depth of about 10 m, with slopes on both sides up to ground surface. The weight of the material above the membrane is now sufficient to be able to lower the water table in the canal without risk of uplift due to the high groundwater pressures below the membrane. The groundwater level in the excavated area must be maintained artificially, by pumping, of course, to balance the inflow due to rainfall and perhaps some leakage through the membrane, but in the Netherlands this is nothing special: in practically the entire country the groundwater level must be maintained at a prescribed level, often below sea level, anyway.

The basic principle of this technique is that, assuming that saturated soil is twice as heavy as water, a soil layer of 1 meter thickness can balance a water pressure of 2 meter. For this principle to work it is essential that the impermeable membrane is indeed located at a depth of twice the final depth of the excavation. In order to ensure sufficient depth of the membrane great care is needed in placing it, see Figure 14. This figure shows a section of the excavation pit, in the direction of its length, which may be several kilometers. The membrane is lowered from a pontoon, and pressed to the bottom of the excavation by a water level difference between the two sections on the two sides of the membrane. Care should be taken to ensure that the water pressure at the bottom of the excavation on the left side is indeed greater than the water pressure at the right side and below the membrane, taking into account the possible differences in silt content of the water on the two sides, which will probably result in the water on the right side of the membrane being slightly heavier than the clean water on its left side. If the water level difference is insufficient the membrane will not sink to the bottom of the pit, but rather float at an intermediate depth, as shown in Figure 14. During the later process of backfilling with sand the membrane will undoubtedly sink, but there is a risk that this sinking process will then be very inhomogeneously, with the possibility of tearing the thin membrane. For this reason the membrane must be placed very carefully on the bottom of the building pit before the backfilling, and its position and integrity should be checked by divers. It should also be noted that the effective stresses just below the membrane are very small, so that the stiffness and the shear strength may be very low.

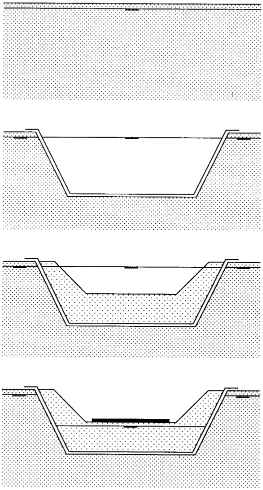

Figure 13: A road below ground surface.

The result of this construction method is an attractive deep-lying road, with naturally looking grassy slopes, see for instance Figure 15, which shows an aqueduct near Grou in

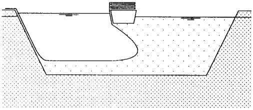

Figure 14: Sinking the membrane.

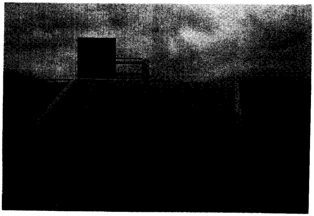

Figure 15: Aqueduct near Grou.

the Province of Frisia. The underpass gives the impression of a simple excavation in dry soil, with gentle and natural green slopes. The deep impermeable membrane cannot be seen, of course, but it plays an essential role in the stability of the structure. This technique has ben used at several locations in the Netherlands, mainly for the entrance of tunnels and aqueducts, but also for railway crossings and road crossings.

8 CONCLUSION

It has been shown, on the basis of a number of examples, that a combination of hydraulic engineering methods with a good understanding of geomechanical principles is needed to satisfy society's need for various structures in the infrastructure of countries with a soft soil and a high groundwater table, such as the Netherlands. Although it may seem that hydraulic engineering methods have reached their ultimate level of application, it can be expected that progress will not stop at the turn of the millenium, and that new and more refined methods will be developed. It is certain that a basic need for a sound understanding of the basic principles and methods of soil mechanics will allways remain needed. It can also be expected that, as in the past, the growing complexity of engineering structures will require ever more insight in and knowledge of the basic principles of engineering mechanics, including soil mechanics.

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