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Geotechnical Effects of Changes in Groundwater Level

Effet Géotechnique des Changements du Niveau de la Nappe d'Eau Souterraine

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SYNOPSIS The waterhousehold and the physical characteristics of soil are functions of the position of the water table, concludingly, a soil will sensitively respond to changes of the groundwater level. Theoretical considerations and examples taken from practice prove that the majority of geotechnical problems can be solved successfully only in the possession of hydrological data.

INTRODUCTION

Generally, the groundwater level fluctuates around a dynamic equilibrium level determined by soil properties and meteorological elements. Due to seasonal fluctuations physical properties of soils change with time and only there average values covering longer periods may be regarded as constant. Even more considerable consequences might occur if, as a result of certain human activities a long-lasting drop or rise takes place in the dynamic equilibrium level.

BEARING CAPACITY OF SOILS

It may easily be seen that in the equation

$$q_o = B\gamma N_\gamma + D\gamma N_q + cN_c \qquad (1)$$

all characteristics except B and D are functions of the relative position of the groundwater level to the level of foundation.

Granular soils

As the shear strength of a granular soil is practically independent of the water content bearing capacity factors do not change with the position of the groundwater. In this case the influence of groundwater appears in the fact that mass unit weight and capillary cohesion depend on sign and size of the neutral stresses.

Mass unit weight is included in the first two terms of Eq. (1) and its change will indicate its influence through the second term primarily. Depending on the position of the water table the bearing capacity of a strip footing (a) in Fig. 1 will fluctuate between 850 and 490 kPa (b). The latter is equivalent with the case where -- with low groundwater level -- the plane of foundation is at a depth of -0.66 m.

Considerable increase is caused by capillary cohesion. If, e.g., $B = 1$ m, $D = 1$ m, $\gamma = 20$ kN/m^3 and $\varphi = 30^o$ then, according to Terzaghi's theorem, $q_o = 660$ kPa and if a capillary cohesion of 4 kPa is also considered then $q_o = 898$ kPa.

When evaluating loading tests the procedure to be followed may be that a) mass unit weight is estimated depending on the momentary position of the water table and b) capillary cohesion is calculated -- using, e.g., Kutzner's (1963) graphs -- by means of d, n and w. The bearing capacity factors may be determined by iteration, accepting the approximation that $N_\gamma \cong N_q$ and $N_c = (N_q - 1)\cot\varphi$.

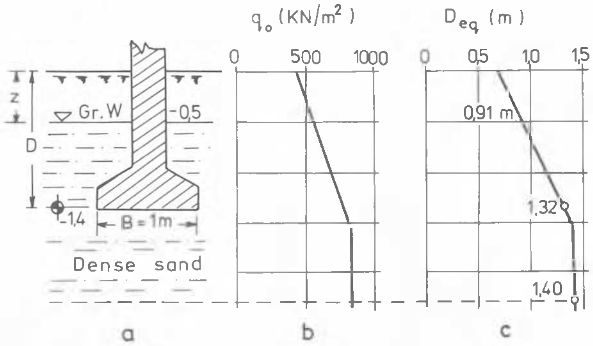

Fig.1. Bearing capacity as a function of the relative position of the water table

Cohesive soils

In this case both the shear strength and the bearing capacity factors will change with the water content. Conclusions on change in cohesion can be drawn from the graphs in Fig.2 (Réthàti, 1973). According to it, the averages of q_u determined from several hundreds of samples show considerable differences in the two categories: for soil samples taken from above the water table q_u was by 20 to 75 per cent higher than for samples taken from below the groundwater level. This is a warning to the designer that a possible future rise of the water level should be taken into account.

The situation is similar when ultimate bearing capacity is determined from tables. If the soil mass underlying footings may be surmounted by the water table the consistency index must be calculated by the formula

$$I_c = \frac{w_L - S'_r \frac{e}{\gamma_s}}{w_L - w_p} \qquad (2)$$

where S_r' is the expected value of the degree of saturation. According to observations cohesive soils are not saturated even under the groundwater level (Fig.3), so in Eq. (2) $S_r' = 0.95$ may be included.

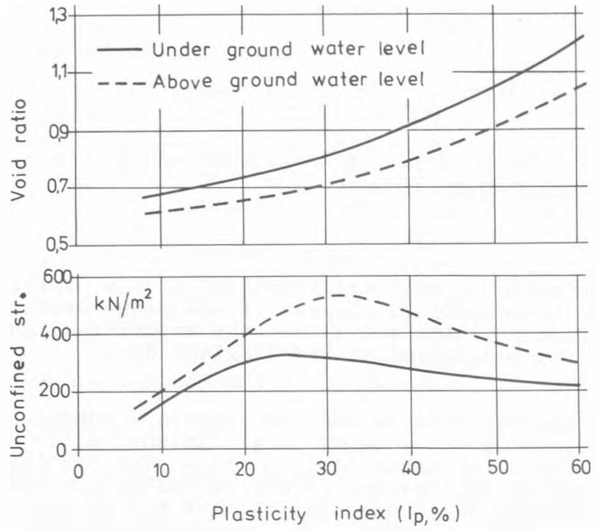

Fig.2. Change of q_u and $\underline{e}$ with I_p

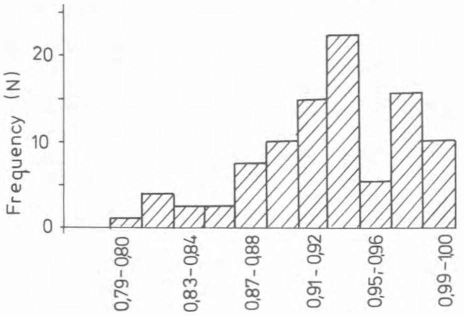

Fig.3. Histogram of the S_r values of a clay located below groundwater level

SETTLEMENT OF FOUNDATIONS

Primarily cohesive soils are affected in their deformation by the water content, and, through this, by the position of the water table.

If groundwater level is low a possibility of desiccation in the upper layers exists. In Fig. 4 the dependence of S_r on depth is shown.

(The 740 samples utilized in it were taken in the regions of Hungary where momentary depth of the water table was at least 2.5 m lower than the plane of sampling.) According to the graph, a potentially considerable worsening of the situation may occur with the rise of the water table after the dead-load has been placed on the soil. To estimate the possible change ΔM in the magnitude of the modulus of compression let us take a start from the empirical relationship

$$M = (160 - 2\, I_p)\, I_c \, . \qquad (3)$$

As a result of water up-take the relativ change in $\underline{M}$ will be

$$\frac{\Delta M}{M}\, 100 = \frac{e \cdot \Delta S_r}{w_L \cdot \gamma_s - e \cdot S_r}\, 100 \, . \qquad (4)$$

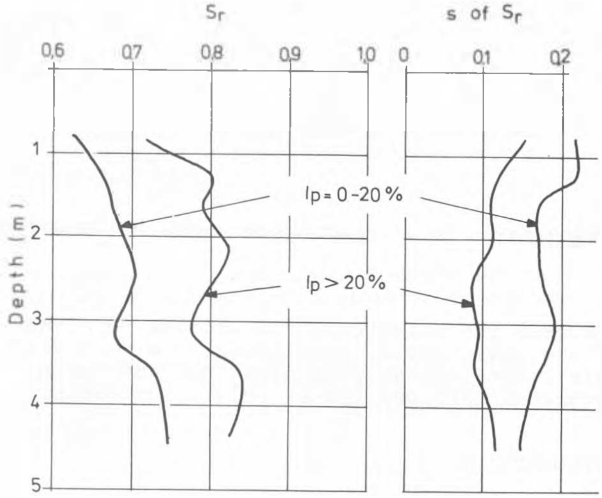

Fig.4. Variation of the mean and standard deviation of saturation with depth (in case of deep moving groundwater)

If $w_L = 50$ % (= 0.5), $\gamma_s = 28$ kN/m^3 and ΔS_r is taken in a way which the initial value of S_r is supplemented up to 0.95 the set of curves shown in Fig.5 is obtained. So, the change of $\underline{M}$ of clays with medium saturation can amount even to 40 - 50 %.

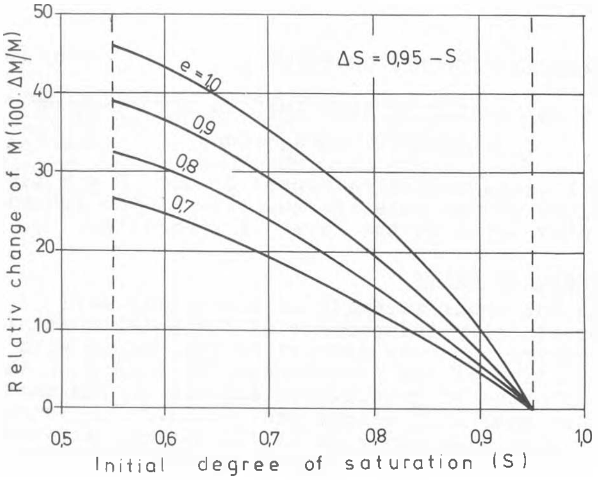

Fig.5. Decrease of $\underline{M}$ caused by an increase of S_r

Swell and shrinkage can also be caused by changes in the groundwater level (see later) and in the case of organic soils in addition, the circumstances of decay process can also be altered.

PROBLEMS OF CONSTRUCTION

High water levels may cause technical difficulties (risk of rise by bouyancy, deployment of piles without casing, concreting in flowing groundwater) and, in addition, a considerable increase in the construction cost. In case of lack of preliminary data the planner is forced to elaborate alternative plans. In many cases the "learn as you go" method proposed by Terzaghi can also be used successfully. A further possibility is the prediction of the water level and a proper choice of the construction period.

Dewatering working pits

With regard on the dewatering of working pits different situations may be developed by the natural fluctuations of the groundwater. This is intended to be demonstrated in Fig. 6: depending on the actual water level four variants can be mentioned and, as a fifth a foundation system by which dewatering is not needed at all.

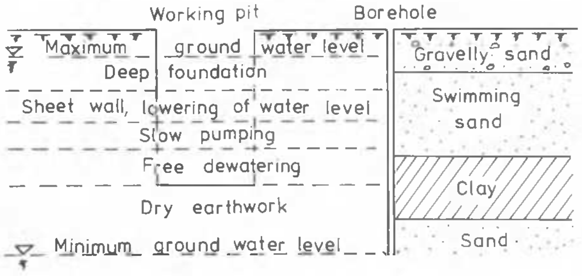

Fig.6. Possibilities for dewatering a working pit in case of a given soil profile

Excavation and foundation may be carried out expediently when the groundwater lies low. In most parts of Europe the highest groundwater level occurs in springtime while the lowest in autumn. According to data obtained from observation wells in Hungary the time of culmination can be calculated from equation

$$t = 17.9\,\bar{W} + 77 \qquad (5)$$

where t denotes the number of days after the 1st of January and $\bar{W}$ (m) the average depth of the water table. The expected time of minimum water level is

$$t = 8.8\,\bar{W} + 267 \qquad (6)$$

which means that the near-surface groundwater level reaches its deepest position on the 27th of September and each further 1 m (below the ground) will cause a lag time of 9 days.

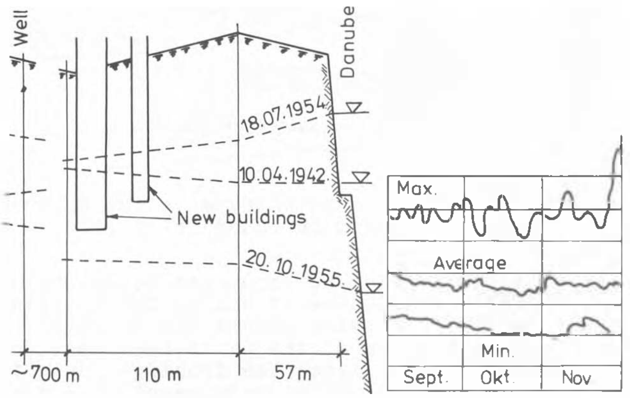

Fig.7. Determination of favourable construction periods near rivers

In the case shown in Fig. 7 the problem was to design the dewatering of a working pit for two storage bins. Along this reach of the Danube is free communication of river-water and groundwater in the fine sand. A statistical analysis proved that there is only a low probability for stages exceeding the plane of foundation between September and November. This "mathematic expectation" came true: during autumn in 1955 foundation was constructed in a dry pit.

In housing estates and industrial plants where the slope of the water table is steep or where the plane of the foundations is varying the economical timing of earthworks within the calendar year is possible (Fig. 8).

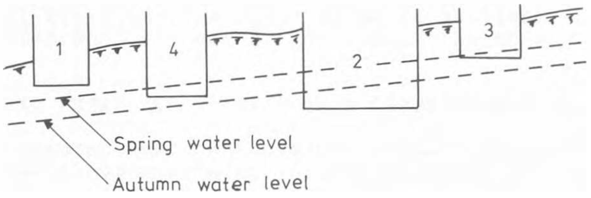

Fig.8. Timing of earthworks with respect to the annual fluctuations of the water table

In practice, the case where different foundation variants are elaborated is not infrequent. In such cases the question how to take cost of dewatering into account may emerge. As a possible solution the compilation of empirical distribution functions of the stages may be selected. In this way the probability α that the plane of foundation will be surmounted by the water table can be determined for each plane. The cost belonging to a certain variant can be calculated by multiplying the total cost of dewatering by α.

If the period of construction is known the expected position of the water table can be predicted by a certain accuracy (Réthâti, 1973).

Construction of earthworks

The efficiency of excavation and compaction is a function of the water content and so the depth of water table during the period of construction is not indifferent.

If excavation is manually performed the lowest level of excavation is determined by the momentary position of the water table. In case of mechanized excavation generally no technological limitation is considered, nevertheless, excavation from below the water table may not always be desirable, because the water content of the excavated material is above the optimum.

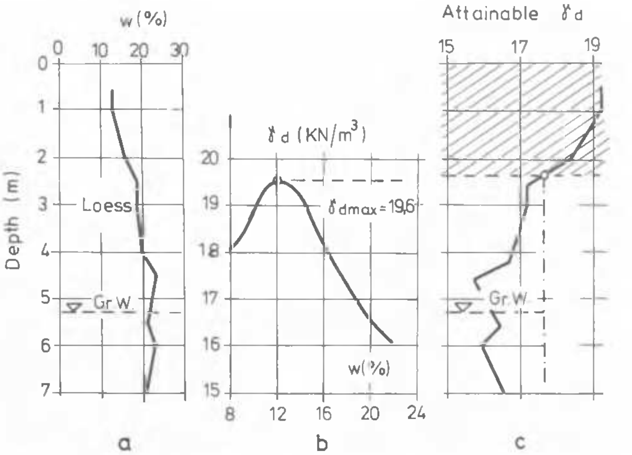

Fig.9. Thickness of the economically compactable soil layer (c) in case of a given soil profile (a) and a given Proctor curve (b)

In Fig.9 a soil profile (a) and the Proctor curve of the discussed loess soil (b) are shown. Calculating on the basis of the water contents the feasible dry unit weight for different depths (c), the conclusion may be drawn that -- by supposing an immediate utilization of the excavated material -- the degree of compactness $T_{r\gamma}$ = 90 % is attained only with soils layered between 0 and -2.35 m. In the course of planning the risk that till the start of construction the position of water table and capillary fringe may undergo changes should also be considered.

SUBSIDENCE CAUSED BY A RISE OF THE WATER TABLE

Affected by water certain soils may undergo considerable subsidence. This phenomenon was observed first with loess soils (Abeljev, Denisov) and the conclusion was drawn that maximum deformation would develop at a load of approximately 300 kPa. According to experiments conducted by Jáky (1948) in loose gravel, a subsidence amounting to 3 - 5.5 % may occur if it is soaked by gravitational water.

More recent experiments (Rétháti,1963 and 1965) prove that in loose granular soils considerable subsidence may be caused by capillary waters. The magnitude of the specific subsidence (ρ) depends on particle size, soil density, saturation developed in the course of water up-take and the load acting on the soil (Fig.10). Unlike to loess here a maximum value of ρ will be attained if q = 0. This is the explanation of the fact that primarily floors and separation walls -- having low rigidity -- are threatened by subsidence.

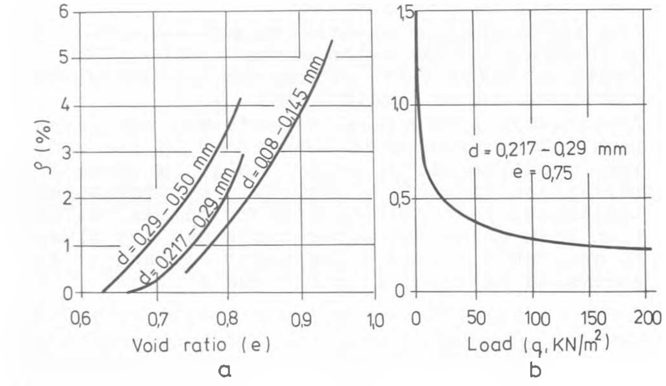

Fig.10. Specific subsidence as function of particle size and void ratio (a) and of load (b)

In one of the power plants of Budapest a building was damaged by gravitational water. High stages in the Danube in the period of 1939/40 caused a rise in the groundwater the result of which was a considerable subsidence in the gravely fill the thikness of wich was 4 to 4.5 m.

The case of the building shown in Fig.11 offered opportunity for a detailed examination of this question (Rétháti, 1977). Both the bearing walls of the crack-netted front and the separation walls stood on a loose fill with varied thickness. Construction had been finished in April, 1964 and damage was first observed in May, 1966 on the separation walls and -- at the end of the same year -- on the bearing wall. Up to the date of examination (May, 1967) a differential settlement Δs = 9.5 cm could be detected by levelling the foot-wall. The examination proved that it was the first case since completion of the fill that it was affected by groundwater. The thickness of the layer inundated (included the capillary fringe) and the measured differential settlement as well as the pattern of the cracks are in good concert. Under the other three unhurted external walls the fill wasn't reached by groundwater which is another proof of the assumption made above.

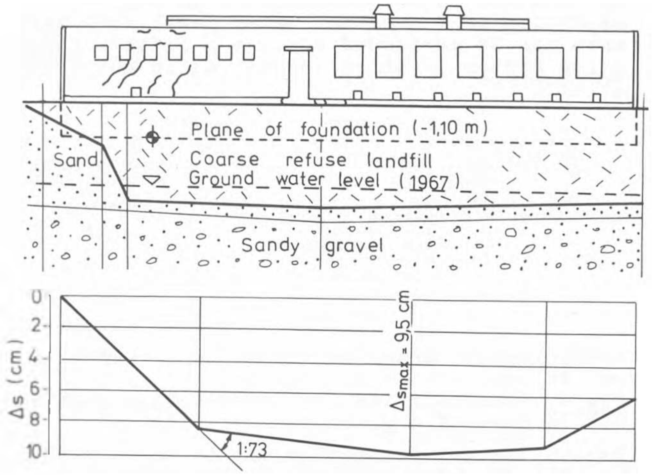

Fig.11. Subsidence of fill caused by the rise of the water table

There is also an example to a case where the level of groundwater rose as a concequence of regulation of a nearby brook. The result was a subsidence of the loess below the building and a serious damage in the structure. Such cases may also be encountered where, following a finished mining activity, the water table returns to the position which prevailed 20 to 30 years before, posing danger to the walls and cellars of the new buildings.

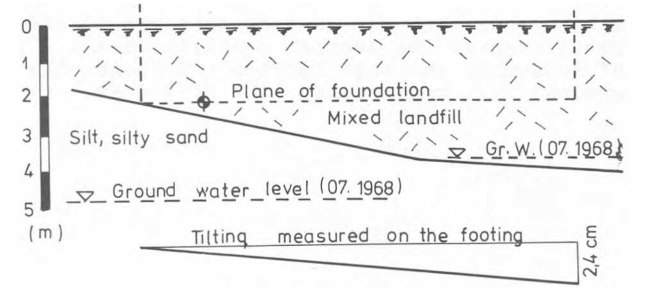

Fig.12. Tilting of a building as a consequence of water table elevation caused by public services

Field tests can also be conducted to determine the specific subsidence of soils. The building shown in Fig.12 existed unhurt for 50 years. In the late sixties on of the walls came apart of the adjacent neck. Along the frontage shown in the figure a differential settlement of 2.4 cm has developed while the settlement of the floor along the bearing walls was 15 - 20 cm. Examination showed that the groundwater level -- just where the fill was thicker -- stood higher than in the adjacent boreholes as a consequence of leakage from the service conduits of the neighbouring building. In the course of a loading test a pressure of 100 kPa had caused a compression of 5.3 per cent and a subsequent inundation a subsidence of 3.7 per cent.

VOLUMETRIC CHANGE CAUSED BY A DROP OF THE WATER TABLE

It is a well-known fact that changes in the soil volume will pose danger to a building if the water table and the hydraulically linked capillary fringe are deep down. In this case the waterhousehold of soil is governed by meteorological elements (precipitation and evaporation) with the consequence of periodically varying swelling and shrinkage. Fig.3 is a proof that due to evaporation considerable desiccation may take place in the top layer.

The degree of danger threatening the buildings is varying from year to year. This may be caused not only by the meteorological elements but also by groundwater. In summer a rapid drop of the water table takes place thus giving gradually free play to the effect of insolation and transpiration. Under our climatic conditions the minimum of the water content is reached in September and it is followed soon by the nadir of the groundwater level. These factors may explain that the damage caused by a change in soil volume (or more exactly by shrinkage) appears always in late summer.

This process is the same in every year. Nevertheless, there may be considerable differences between individual calendar years depending on the culmination level of groundwater in springtime. In Fig.13 a situation developed around an observation well is shown. The sector of soil under the plane of foundation was saturated in 1940 and 1941 while during the preceding four years its water content had been governed merely by precipitation and evaporation.

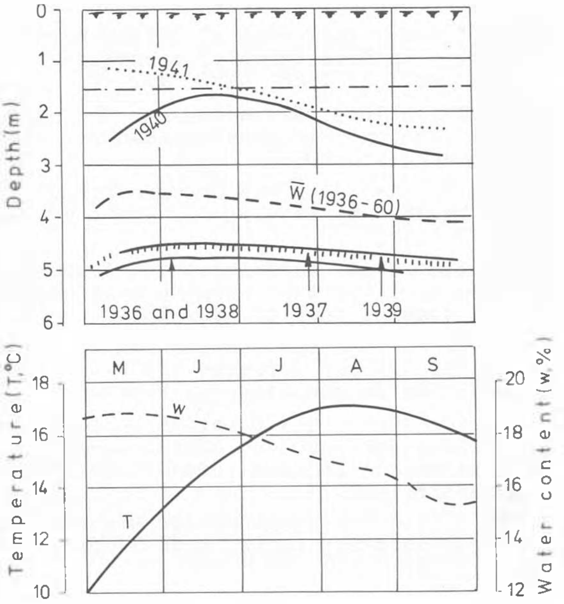

Fig.13. Circumstances of soil shrinkage within a year and in multiannual relation

From Fig. 13 the conclusion may be drawn that the danger of volumetric change depends also on the position of the water table during construction. In a case, e.g., where the constructing a building was in summer in 1938 further shrinkage cannot be expected so that only the possibility of swelling must be examined.

Temporal coincidence was experienced between the deterioration of a monument-like church and the regulation of a nearby river. Following the latter, the groundwater level had decreased and the formerly frequent inundations stopped. Concludingly, in the unevenly loaded heavy clay shrinkage took place and the nave was to be taken down and the tower fastened.

In a housing estate consisting of one-storied buildings damages were observed after a water inrush in a shaft at a nearby mine followed by a rapid drop of the water table. Cracks or deformations could be found on those 77 buildings which had been founded on black heavy clay.

CONSEQUENCES OF WATER TABLE FLUCTUATIONS

Behavior of foundations

When the groundwater level is dropping the dead weight of the layers will increase. The soil is disencumbered by the rise of the water table, however, the magnitude of expansion will be smaller than that of the preceding compression. This may explain the experience that a settlement may be caused by the fluctuations of the water level although in many cases probably a contribution to this phenomenon is given by a gradual rearrangement of the particles, too.

Numerous examples proved that extremely large-scale surface movements can be resulted by sharp drops of the water table (Long Beach, Santa Clara Valley, Mexico City, etc.) Only a few examples can be found for cases where the movement of the foundation has been caused by a smaller fluctuation of the water level. The evaluation is made difficult also by the fact that this movement doesn't appear separately but superimposed on the consolidation or other effects (e.g., the volumetric change of soil).

Bernatzik (1947) presented a building in the port of Le Havre, situated at a distance of some 100 m from the coast, which, affected by the tidal motion amounting to 6-8 m displayed a motion with an amplitude of 5 to 6 mm.

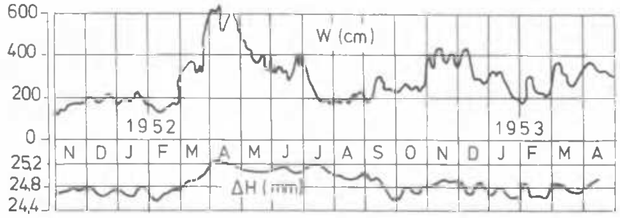

Fig.14. Relationship between the elevation difference of two geodetic posts (ΔH) and the stages in the Danube (W)

At the Technical University of Budapest the elevation of geodetic posts has been measured for several years. They are standing on a block-wall of 1.8 x 25 m^2 located perpendicular to the stream line of the Danube and founded independent from the bearing walls. There is a detectable response in the difference between the elevations of the posts to the fluctuations of the stages in the Danube (Fig.14). Through this correlation an accuracy of ± 0.07 mm could be attained in determining the movement of the posts.

Corrosion of foundations

The quantity of aggressive components is a function of the groundwater level. At an observation station in Hungary monthly measurements of the SO_4 content of the groundwater had been conducted through 4 or 5 years. According to these measurements the regression equation representing connection with depth ($\underline{z}$, m) was

$$SO_4 = 752 - 282\ z. \tag{7}$$

So, the depth of the water table at the date of water sampling is not indifferent. In addition, when prescribing protection, the zone of scattering around the regression line ranging to 15 - 20 per cent, should also be considered.

Mouldering of timber piles

If a timber pile is kept continuously underwater it will remain intact for centuries. The situation is different if a pile is placed into the zone of water table fluctuations or if the groundwater level decreases for a longer period.

In a Hungarian city, Sopron, old sewers made of brick had replaced in the twenties by concrete and stoneware tubes, respectively. As a result a large-scale decrease of exfiltration took place which in turn resulted in a long-lasting drop of the water table. It was only 2 or 3 decades later that the reason came to light, namely, the timber piles of monument buildings which had been standing intact for 150 to 300 years started to moulder except those kept underwater.

In New York City at an eleven-storey building a differential settlement of 5 cm was developing because construction around it caused a continuous lowering of the water table. As a consequence of mouldering of the timber piles a cavity was developed over an area 9 m^2, with a depth of 40 to 60 cm. In the city of Kearny a chimney of 23 m was threatened by collapse because of a differential settlement of 7.5 cm caused by the mouldering of timber piles (Mc Kinley, 1964).

ROLE OF GROUNDWATER IN THE DAMAGE OF BUILDINGS

The role of groundwater played in causing damage to buildings is active or passive. In the first case damage is caused by the presence or movement of gravitational water, while in the second the influence is indirect: harm is made possible just by the situation that water table is located under the plane of foundation.

So the most frequent types of damage may be ranked into three groups:

1. water table fluctuations, forced pumping, frost penetration (active role);
2. break of sewers and delivery pipes, water flowing down from roof, surface water, volumetric change of soil (passive role);
3. heat effect, uneven settlement, dynamic effects, overload, repeated load, landslide, deformation of cavities, undermining (the position of the water table is indifferent).

According to a Hungarian statistics (on the basis of 800 damaged buildings), 6.3 per cent of the cases may be ranked into the active category while the passive one included 72.4 per cent. So the probability of damaging is favourable if the plane of foundation is exceeded by the groundwater level. This may explain that the probability of damging in plainlands is one-third of that observed in mountainous and hilly regions. On the considerable passive role of the groundwater conclusions can be drawn from the statistical data of other countries, too (Logeais, 1971).

CONCLUSIONS

The change in the position of the water table and of the connected capillary fringe causes a change in numerous physical characteristics of the soil. The consequence of this is that the position of the water table exerts a considerable influence on the bearing capacity and deformation of the soil, on the stability and solidity of foundations and on the circumstances of construction of earthworks. This is referred to by the examples and by the statistics of damaged buildings according to which in 80 per cent of the cases groundwater had a decisive role.

From these the important conclusion may be drawn that the planner should have information about the dates of annual extremities, the frequency of the water levels and the maximum and minimum groundwater levels to be expected during the life of a structure.

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