LAND SUBSIDENCE IN SWEDEN DUE TO WATER-LEAKAGE INTO DEEP-LYING TUNNELS AND ITS EFFECTS ON PILE SUPPORTED STRUCTURES

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Abstract
Extensive damage on buildings and other structures have been caused in Sweden by a lowering of the groundwater level due to water-leakage into deep-lying tunnels in rock. Other factors such as deep excavations, large trees, changes of the climatic conditions have affected the groundwater level as well as the reduced recharge of water when streets, sidewalks and parking-lots are paved.

Buildings supported in timber piles have been damaged when the piles are exposed above the groundwater level and start to decay. Subsidences can increase the load in piles below a building due to negative skinfriction, since the piles will carry part of the surrounding soil. This increase of the load can be so large when the compressible strata are thick that the compressive strength of the piles is exceeded.

Batter or raked piles are frequently used in Sweden to resist lateral loads. Even a moderate subsidence can increase the maximum bending moment in the piles just below the pile cap so that the yield strength of the reinforcement is exceeded. Subsidence has also caused pile failures due to the lateral displacement of the soil under a building.

Different methods can be used to decrease or to eliminate the subsidence, e.g. preloading of the soil, pregrouting of the tunnels or injection of water.

Underground construction in Sweden
Sweden has old traditions in mining and underground construction. Internationally Sweden is one of the leading nations with respect to the volume of excavated rock per capita. The total volume exceeded 26 Mm³ in 1974. The mines accounted for about 85% (23 Mm³). Each year more than 35 km of tunnels are constructed in urban areas for traffic, service lines (water, sewage etc) and to a certain extent for storage (Jansson and Winqvist, 1976). Fig. 1 shows the tunnel-system in the region of Stockholm. The tunnels have in many cases caused extensive subsidence due to a lowering of the groundwater. Subsidences of 20 to 40 cm are common. Especially deep-lying tunnels have caused serious problems.

Geological conditions
About 95% of the bedrock in Sweden consists of crystalline rock, which in general is very favourable for underground constructions because of its high strength and the fact that the loose and weathered parts at the surface have been removed by the ice during the glaciation. Depressions in the rock surface are in most places indications of tectonic zones in the underlying rock which have been eroded and deepened by the land-ice.

After the latest glaciation parts of Sweden were covered with water, fig. 2. During this time clay and silt were deposited partly as products from the melting land-ice, partly from redeposited and outwashed material during the land upheaval. The clays and silts were deposited in many places over a thin layer of till or sand and gravel on the surface of the bedrock. The areas covered by clay are rather small as shown in fig. 2, but the urban regions in Sweden are to a great extent situated in these areas.
Hydrogeological conditions

A section through a clay-filled valley is illustrated in fig. 3. Deep-lying tunnels act as drains, particularly in tectonic zones which lower the pore water pressure first in the pervious bottom layers (confined aquifer), and then gradually in the overlying clay layer. The permeability and storage coefficient of the aquifer is usually about $10^{-6}$ to $10^{-5}$ m/s and $10^{-5}$ to $10^{-4}$, respectively. The leakage rate varies but is in general small. However, the total volume can with time be large as well as the area affected by the lowering of the groundwater table. The size of the affected area ($500$ m$^2$ to $1$ km$^2$) depends on the topography and the lateral extent of pervious layers.

The initial pore water pressure in the soil before the construction of a deep-lying tunnel increases normally linearly with depth. The groundwater level for the surface layers is normally the same as for the pervious bottom layers as illustrated in fig. 3a.
Fig. 3. Effect of a lowering of the groundwater level on the pore pressure in a deep clay layer.
In general, this groundwater level is not affected since these layers are normally not in direct contact with the pervious bottom layers. The resulting high excess pore water pressures in the clay will gradually decrease with time as indicated in fig. 3b. Ten to thirty years may be required before the excess pore water pressures have fully dissipated, when the thickness of the clay layer is relatively large and the clay does not contain any continuous sand or silt seams.

The effective stress in the clay and the subsidences gradually increases when the pore water pressure and the water content of the clay decrease. The shaded area to the left in fig. 3b indicates the pore pressure distribution after several years when the excess pore water pressures in the clay have dissipated. The change of the pore water and of the effective pressure in the clay layer will be large. A flow rate of only a few millimeters per year in the clay from the surface layers can be expected. In fig. 3c, the groundwater level has been lowered in the surface layers, e.g. by pumping from a deep excavation. This will only have a moderate effect on the pore water pressure in the clay in comparison with a deep-lying tunnel. The subsidences will in general be relatively small. The shaded area to the left in fig. 3c indicates the pore pressure distribution after equilibrium has been reached and the excess pore water pressures in the clay have fully dissipated. A leakage from the pervious bottom layers through the clay up to the surface layers will be the result.

The effects of a lowering of the groundwater level have been studied by Torstensson (1975a) for different boundary conditions. The change of the pore water pressure with time has been calculated in fig. 4 for a 15 m thick clay layer which is located on a pervious sand layer. The groundwater level has been lowered 6 m. The indicated isochrones have been calculated for one-dimensional flow.

Evaluation of subsidence

The glacial and postglacial clays in Sweden are comparatively young. They are normally consolidated to slightly overconsolidated. The water content of the clays is high (>60%), while the shear strength is low, often less than 20 to 30 kPa. The compressibility is high and even a relatively small change of the piezometric level can cause large subsidences.

The groundwater level in Sweden can vary appreciably between different years as well as during one year, depending on hydrometeorological and geological factors.

The groundwater level in the surface layers is in general at its highest in the spring during the thawing period and reaches its lowest level early in the spring just before the thawing period. The yearly variations of the groundwater level can vary from a few centimetres to several meters. Numerous structures were damaged in Sweden during the dry summers in 1947 and 1955 because of the exceptionally low groundwater level (Hellgren, 1959). Also in 1976 the damage was extensive.

The subsidence can be calculated from the change of pore water pressure or of the piezometric head and the compressibility of the soil. Pore pressure sounding instruments have been developed as well as improved pore pressure gauges, so that the effects of a lowering of the groundwater level can be calculated (Torstensson, 1975a). Pumping and injection testing methods, which can be used to analyse the hydraulic properties of aquifers (Carlsson, 1973, Carlsson and Kozerski, 1976), and the deformation properties of deep-lying clay layers (Alte, 1976) fig. 5 have been improved. Numerical models are used to evaluate the influence of different factors and the effectiveness of various methods which can reduce or eliminate the subsidence.
A decrease of the groundwater level has the same effect as an externally applied load. The subsidence from a 1.0 m thick fill will be about the same as that from a 2.0 m lowering of the groundwater level. Examples of subsidence calculations are shown in fig. 6 for different thicknesses of the compressible layer (Torstensson, 1975a).

The subsidence rate depends to a large extent on the permeability and the thickness of the different strata. Ten to thirty years are normally required before the consolidation has stopped, due to the low permeability of the clay ($10^{-10}$ to $10^{-11}$ m/s).

Continuous pervious sand or silt layers in the clay will affect the rate of the subsidence. The real subsidence rate is in general considerably higher than that calculated, mainly because of the difficulties to evaluate correctly the drainage conditions. A pervious sand or silt layer, located at the center of an impervious clay layer, will increase the subsidence rate four times and the time required to reach a given subsidence and degree of consolidation will only be 25% of the time estimated without this pervious layer at the center. It is not certain that sand or silt layers will affect the settlement rate, since it may be entirely enclosed in the clay and has no contact with the pervious bottom layers.

Overconsolidated clays are frequently fractured which will also affect the consolidation rate. The rate of subsidence in organic soils, especially peat, is often considerably lower than that estimated from oedometer tests due to creep (secondary consolidation).
Fig. 5. Changes in piezometric levels in clay and subsidences during a pumping test in the Angered area, Gothenburg (Alte, 1976).

The groundwater level can be lowered by other factors than leakage to tunnels. The rebound after the glaciation (land upheaval) has resulted in an apparent lowering of the groundwater level which has caused problems in the Old Town ("Gamla Stan") in Stockholm. Also the reduced recharge of rain water, when streets, sidewalks and parking-lots are paved, affect the groundwater as discussed e.g. by Hellgren (1969) and Gustafson (1970). The groundwater level is also influenced by growing trees, deep excavations, drain pipes and sewer lines.
Damage caused by subsidence

Lindskoug and Nilsson (1974) have investigated the damage from subsidence during the years 1966 to 1973 due to leakage to tunnels. Buildings are for example damaged when the differential settlement exceeds 1:200 to 1:500. Water and sewer lines rupture when the total subsidence is larger than about 15 to 30 cm (Broms, 1966, 1973). The damage caused by differential subsidences depends not only on the magnitude, but also on the rate of the subsidence and on the building material. Wooden houses as well as brick buildings, where lime has been used in the joints, can tolerate relatively large differential subsidences without damage (1:200 to 1:300). Brick structures, where cement mortar has been used can be severely damaged even by moderate differential settlements (1:300 to 1:500). Doors and windows become difficult to open and it is possible to "feel" that a floor is not level when the slope is larger than about 1:150. High rise buildings are often affected even when the differential subsidences are small, 1:500 to 1:100.

Uneven subsidence also changes the load and moment distribution in statically indeterminate structures as has been studied e.g. by Beigler (1976). The maximum bending moment in beams and columns can increase several hundred percent by differential subsidences. Even the direction of the moments can change. Timber piles and wooden grillages start to rot when they are exposed above the groundwater level. (Broms, 1973, Lindskoug and Nilsson, 1974). The bearing capacity of timber piles can be reduced already after a few months of exposure, particularly in areas where the ground temperature is high, e.g. below furnaces and where the groundwater has been polluted by sewage.

The load in the piles below a pile supported structure increases when the surrounding soil subsides (Broms, 1973). The piles will also carry part of the surrounding soil. This increase of the load in the piles, due to negative skin friction, depends among other factors on the magnitude of the subsidence, the shear strength of the surrounding soil and on the thickness of the compressible layers. Test data indicate that the negative skin friction for cohesive soils can be up to 20 to 25% of the effective overburden pressure. This means that the load increase due to negative skin friction can be as large as 400 to 500 kN (40 to 50 MPa) for a 30 x 30 cm point bearing precast concrete piles driven through a 20 m clay layer, with
the groundwater level located at 2.0 m below the ground surface. The axial load in a pile can thus be more than doubled due to negative skin friction when the length exceeds 20 to 25 m.

Measurements on two instrumented precast concrete piles, which have been driven through a 40 m deep clay layer at Bäckebol about 20 km north-east of Gothenburg, indicate that the axial load in the piles has increased by 400 kN (40 Mp) after six months because of negative skin friction. The subsidence of the surrounding soil was small (2 to 3 mm). After two years, the increase was 550 to 600 kN (55 to 60 Mp) (Fellenius and Broms 1969, and Fellenius, 1971). After eight years, when a fill was placed around the piles, the negative skin friction had increased to 800 kN (80 Mp).

Mainly the piles at the periphery of a structure are affected by negative skin friction. The increase of the load in the center piles of a pile group will be small, when the piles are closely spaced, since the weight of the soil enclosed by the group is distributed between several piles. When the strength of a pile is exceeded at the pile point due to negative skin friction, the behaviour changes from that of a point bearing to a friction pile. The subsidences of the pile will be approximately the same as that of the surrounding soil. The supported structure can then be damaged by the resulting differential subsidences.

Batter piles (raked piles), which are not vertical, can be damaged and may fail when the surrounding soil settles. Such piles are frequently used below road embankments to resist the lateral earth pressures in the embankments or below buildings or other structures to resist for example wind loads. Since the lateral resistance of a pile in soft clay is low, the lateral deflection of the pile will correspond to the subsidence of the surrounding soil. The maximum bending moment in the pile can be so large that the yield strength of the reinforcement is exceeded even when the subsidence is moderate as shown by Broms and Fredriksson (1976). Batter piles should be avoided when large subsidences are expected. Any lateral loads acting on a building can be resisted, for example by a concrete skirt which extends into the soil below the building.

Extensive damage on existing structures has been observed in Stockholm and in the surrounding suburbs as illustrated in fig. 7. At the Maria Square ("Mariatorget") in Stockholm (Tyrén and Sund, 1970), the groundwater level has been lowered with about 3 m since the turn of the century. This decrease of the groundwater level has been caused by water leakage to deep-lying tunnels and by reduced rechange water.

The subsidence that has occurred at Karlaplan in Stockholm is an example of moderate leakage into a deep-lying tunnel, causing extensive lowering of the groundwater level (Morfeldt et al, 1967). There a thin layer of sand and moraine is located at the bottom of a through in the bedrock which functions as a drain for the overlying up to 30 m thick layer of clay. Many of the structures, which were built in the area at the turn of the century, have been damaged. Water and sewer lines have ruptured. It has therefore been necessary to reconstruct the streets and the side walks.

A lowering of the groundwater level of up to 5 m has been observed around the Municipal Court Building ("Rådhuset") in Stockholm (Tyrén, 1968, Sund, 1970) which has partly been caused by deep-lying tunnels. The total leakage to the tunnels is about 70 m³/day which corresponds to a theoretical subsidence of 20 cm/year from consolidation, if there is no infiltration of rain water.

Large subsidences have also been observed at Huddinge Center, located about 10 km south of Stockholm, which have been caused partly by a lowering of the groundwater level and partly by a fill which was placed over the...
area before the construction of the center. The height of the fill has gradually been increased in order to maintain the initial elevation of the ground surface. When the weight of the fill exceeds a critical value, which depends on the shear strength of the underlying soft clay, the soil and the piles below a building are laterally displaced, as illustrated in fig. 8. This occurs when the weight of the fill at foundation level exceeds $5.5 \, \sigma_u$, where $\sigma_u$ is the undrained shear strength of the soft clay as determined e.g. by vane or unconfined compression tests. A lowering of the groundwater level affects the settlements, not only outside a pile supported building, but also below the building so that a void is created below the basement floor.

Damage due to the lateral displacements of the subsoil can be prevented by using light backfill material, e.g. expanded shale ("Leca") or by supporting the fill on separate piles around the perimeter of the structure. These embankment piles will also reduce the negative skin friction on the main structural piles below the building.

**Prevention of subsidence**

The factors which affect the subsidence and methods which can be used to prevent subsidences caused by water leakage into tunnels have been studied intensively in Sweden during the last ten years as well as the legal aspects of the problem (Jansson and Winqvist, 1976).

Precautionary measures can be taken: a) before the construction of a tunnel by avoiding areas which can be affected by subsidence, b) during the construction by e.g. pregrouting, c) after the construction of a tunnel by grouting in order to reduce the leakage or by artificial infiltration of water to maintain the pore water pressure in the compressible layers.

It is often possible to decrease the subsidences in soft clays by preloading. A fill is then placed over the area and is removed when the
subsidences have stopped which may require several years. The additional
settlements from a lowering of the groundwater level will then be small as
long as the increase of the load from the lowering of the groundwater
level is less than the weight of the fill. Preloading can only be used
where the compressible layers are relatively thin or the soil is stratified
so that the subsidences occur relatively rapidly.

It is also possible to preload the compressible layers in advance by
temporarily lowering the groundwater level by pumping from deep wells.

Subsidences due to a lowering of the groundwater level can also be re­
duced by removing part of the soil above the groundwater level. This method
has been used for example in Linköping.

The leakage that can be allowed in a tunnel depends primarily on the
landuse within the area affected by the lowering of the groundwater level.
The maximum rate is often limited to one litre per second and kilometre of
tunnel. Even this low rate can be excessive in sensitive areas. Experiences
with tunnels in Gothenburg indicate that pregrouting in combination with
postgrouting using cement can reduce leakage to only 0.2 litre per second
and kilometre (Lysén and Palmquist, 1976). Good results have also been ob­
tained with silica, lignin and plastic grouts (Bergman et al, 1975).

Attempts have been made to inject water into the pervious bottom
layers through wells where a lowering of the groundwater level has occurred
(Gedda and Riise, 1976). Fig. 9 shows the effect of tunneling and water
injection on the piezometric level in an area in Gothenburg. Water has also
been injected through boreholes into the fissured rock beneath the pervious
bottom layers from pressurized tunnels (Bergman, 1976). This method has
proved very effective.

It has been possible to control the groundwater level in a one-square
kilometre large area at Botkyrka, located close to Stockholm, by injecting
3 litres of water per second through a 2-inch perforated steel tube.
Leakage

Piezometric level

Fig. 9. Change in piezometric levels due to leakage to a tunnel and due to injection of water [Gedda and Rilse, 1976].

a. Map and section over the area (1, 2, 3 and 4 are injection wells).

- - - - - - groundwater level before tunneling

- - - - - - before injection

- - - - - - during injection.

b. Leakage into the tunnel, piezometric levels and injection capacities.

Clogging in and around injection wells has been observed. Both the injection rate and piezometric head in the aquifer are thereby reduced.

Tunnels have also been used as injection galleries. The piezometric level in the bottom layers can hereby be closely controlled through boreholes which are connected with a water reservoir. In one area, the total costs of a tunnel, when used as an injection gallery, was approximately one tenth the estimated costs of underpinning due to the subsidence (Andréasson et al, in print).

Reference areas are required in order to evaluate whether a change of the groundwater level is caused by a change of the climatic conditions or
by a deep-lying tunnel, adjacent excavations or service lines etc. Such reference areas ("groundwater crosses") have been established close to Stockholm and Gothenburg which are representative of the virgin conditions within the regions.

For the planning of a region or a municipality it is necessary to have extensive information of the initial soil and groundwater conditions from boring and observation wells, so that the effects of a lowering of the groundwater level can be evaluated. It is essential that detailed engineering-geological and hydro-geological maps are available. A recent development in Sweden is land and foundation cost index maps, which show the relative cost in an area for different types of foundations. These maps are very useful in the different planning stages (Johansson and Lindskoug, 1971, Lindskoug and Nilsson, 1974).

References


