Soil deformation as a result of fluctuations in the moisture content as a cause of damage in buildings on clay

Déformations des sols et dégâts subis par les bâtiments la cause de variations de la teneur en eau de l'argile

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ABSTRACT: Different soil deformations in the region to the South – East of Braunschweig (Northern Germany) have in some instances led to difficult damage to historical buildings over the past 10 years. Both new and old buildings are equally affected. More detailed investigations in the areas around the churches in Hedeper, Gilzum, Wittmar and Uehrde have revealed that both shrinkage and swelling processes are involved in the solid. The subsoil in many places in this region make up which distinctly plastic clay soils. The soils possess no extraordinary properties and are saturated. The principle and the actual cause for the increasing levels of damage did not fit into the conventional approaches to the mechanics of soil.

RÉSUME: Depuis 10 ans, les déformations des sols au sud – est de Brunswick ont provoqué des dégâts dans des édifices religieux historiques. Des études détaillées ont pu être menées dans les églises de Hedeper, Gilzum, Wittmar et Uehrde. Le sol est construit à base d´argile de consistance plastique. Les sols sont saturés et ne contiennent plus qu ` une très faible proportion de minéraux argileux capables de gonfler.

1. INTRODUCTION

Since the beginning of the 1980s, frequent events of crack damage have been observed in South – East Lower Saxony (Northern Germany). Affected are not only old but also new buildings (figs 1, 2).

In all cases the buildings were raised on strongly cohesive soils of mostly stiff to semi-solid consistency. The building foundations were usually laid on distinctly plastic clay. Closer observations in the vicinity of affected churches in the Villages of Hedeper, Gilzum, Wittmar and Uehrde do not give any indication of unusual ground conditions. The investigation of the mechanical properties of the soil did not show any extraordinary peculiarities. For instance, the amount of dilative clay minerals is negligible.

In consideration of the existing tectonics and regional hydro geological conditions, crack damage in the effected areas can only be caused by the fluctuating moisture content of the clay.

Fig. 1: Map about germany

An analysis of the climate data provided by the German Weather Service in conjunction with the regular observation of building damage demonstrated that the soil deformations are apparently subject to seasonal fluctuations; they include both settlement due to shrinkage and ground heave due to swelling. In-situ measurements of the soil moisture content taken over a period of 60 months indicate a fluctuation of max. 3% by water quite near the measurement site in Gilzum. The analysis of this shrinkage indicates that the solid clays remain saturated throughout the year. Furthermore, high swelling pressures apparently develop. If sufficient moisture is available, such swelling pressure balances previous deformations due to shrinkage even with increased building loads.

Some of the effected buildings are more than seven centuries old; they heave been subjected to natural climatic fluctuations and therefore drier and moister years. There has been building damage in the past, but the damage of recent years apparently pass that of previous times. In the village of Hedeper the church was demolished since its stability could no longer be guaranteed. In Gilzum, Wittmar and Uehrde the stability is guaranteed at this time, but in order to clarify the problem, a fundamental theoretical analysis of the clay soils became necessary.

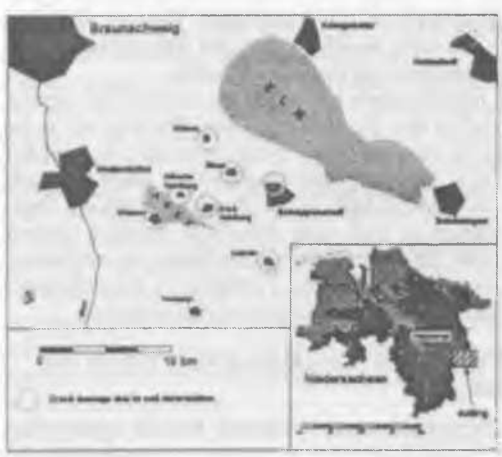

Fig. 2: Investigation areas

2. THEORETICAL STUDIES

Clay minerals are components of natural clay soils. They form extremely fine grained mixtures with large specific surfaces which represent the specific properties of the clay. Clay soils have developed in genetic processes over the course of geologically relevant periods of time. Such process resulting in different pore space structures and the cross-sections of which are extremely small. Under consideration of its molecular size and its specific properties, water may penetrate these pore spaces and, as a result, is henceforth subject to the electrochemical force of the ground mass. The magnitude of this absorbation forces in such cases is considerable and determines the swelling behavior and soil moisture movement in unsaturated and, in some cases, in saturated soils too (Hartge & Horn 1991, Schachtschabel et al. 1992).

Soils are in the scientific literature saturated or unsaturated. Saturated soils generally contain positive pore water pressure and unsaturated soils negative pore moisture tension. Considerations of soil physics imply that extremely fine – grained soils remain saturated during shrinkage processes (for a certain range of their moisture content) since air cannot physically penetrate the pore system. These soils exhibit negative pore moisture tension in this process. Therefore, distinctly plastic clay soils in the humid climate zone of northern Europe near the Earth's surface occur in a quasi – saturated state.

Changes in the forces acting upon soil moisture occur near the Earth's surface due to the influence of climatic processes in conjunction with local conditions (topsoil, fauna, morphology); these usually lead to soil deformations (Cen 1975, Boden & Driscoll 1987). In this process, clay soils react in the same way, but to a different degree owing to differing pore space structure and mineralogical composition. Buildings are subjected to the deformations of the ground on which they are erected. Differing amounts of heave or settlement may lead to bending or twisting of the sub grade surface. If the stresses which can be absorbed are exceeded, the cracks occur (Rybicki 1978). The type and extent of the deformation may be deduced from the fracture pattern.

The analysis of the mechanical behavior of clay soils shows a complex connection of cause and effect. While even small changes may lead to considerable soil deformations in their vicinity, for instance in fauna, large interventions, under certain local conditions, may sometimes have no effect. In the final analysis, the extent of change depends on local conditions. Generalizations and the arbitrary transfer of observations results is not possible.

3. LABORATORY EXPERIMENTS

The aim of the laboratory experiments was to observe the mechanical behavior of existing clay soils under definable conditions. To do this, the natural conditions had to be represented as accurately as possible in a test experiment. The use of undisturbed samples is a basic condition for such testing because the internal fabric determines the hydraulic routings.

Hence, this internal fabric has to remain constant throughout the water adsorption and draining processes. The clay soil to be examined reacts to changes in the moisture content by changes in its volume. It is completely saturated and the observable differences in its moisture content lie far above its shrinkage limit. The volume changes in such soils with these moisture content values are uniaxial. Under the existing conditions, the oedometer proved to be appropriate apparatus. Furthermore, the oedometer test was extended by measuring the pore moisture tension.

3.1. Analysis between the relationship of water tension and moisture content

The result of the experiment shows clearly that the relationship between water tension and moisture content is dependent on the initial dry density (fig. 3).

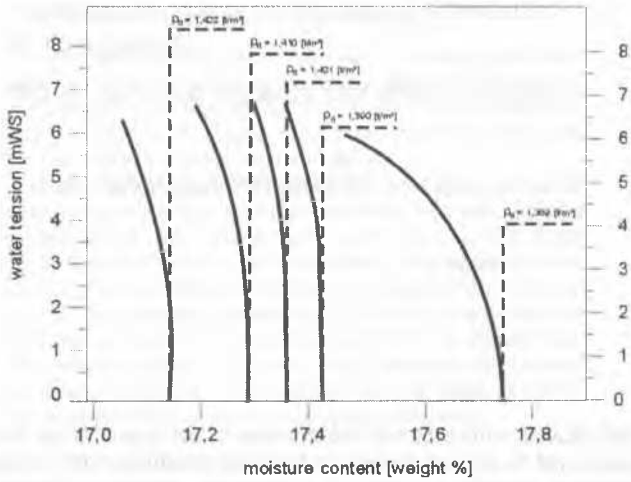

Fig. 3:Ton Wittmar, relation between the water tension and moisture content in addition to the initial dry density

In addition, the level of the pore moisture tension changes with the surcharge on the ground.

Further experiments on the variation of dry density and uniaxial compressive strength, depending on the depth of the sample's location at the village of Gilzum, Hedeper, Uehrde and Wittmar demonstrate that the macroscopically homogeneous clays possess considerable non homogenities. Therefore, for these clay soils there is no universally valid relationship between water tension and moisture content which could even to some extent explain the actual ground conditions in the soil of the building site.

3.2. *Swelling pressure and suction tension*

Swelling effects caused by water accretions or water inclusions is a reaction to electrochemical force relationships in the pore spaces. Swelling potential is therefore determined by the same factors which determine water absorbation. Every cohesive soil, if prevented from expansion (in the process of swelling), build up swelling pressure. In this process, the pressure is equal to the force which affects the surface with which the soil attracts the last water molecules (Hartge & Horn 1991). From the point of view of soil mechanics, pore moisture suction develops relative to atmospheric pressure. Every swelling process is therefore to be understood as the soil reacting to existing pore moisture suction. The experiments confirm that a saturated clay sample, with

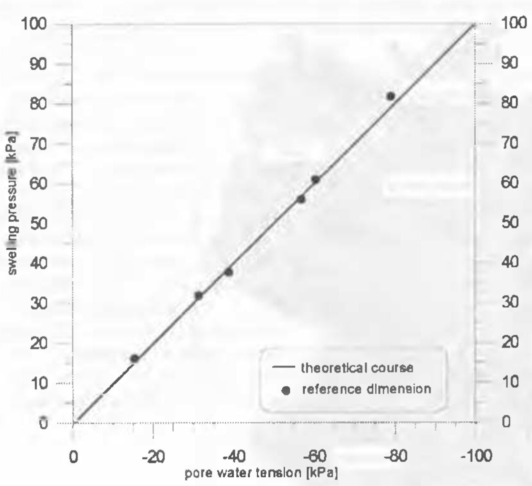

Fig. 4: Theoretical course and reference dimension from the relation swelling pressure to pore water tension of the saturated „Gilzum Clay".

The cause of some noteworthy swelling pressure development in clay soils is to be found in this process.

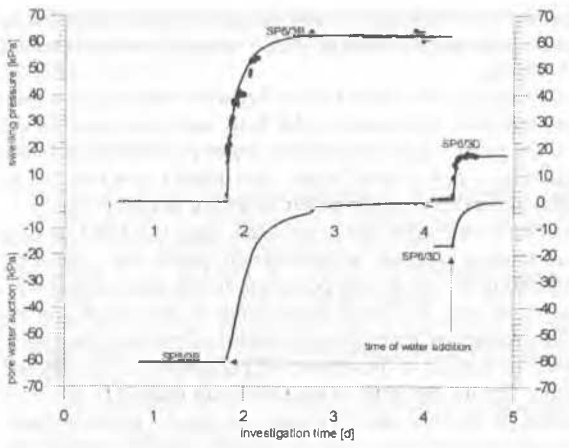

Fig. 5: Swelling pressure and pore water suction in correlation to time of water addition

water addition and inhibited expansion, exerts precisely that pressure on its environment which corresponds to the level of suction tension at the time of water addition (fig 4).

3.3. *Suction tension in situ*

The relationship between swelling pressure and suction tension is the actual cause of cyclic swelling of the saturated clay soils. The development of the suction tension in the case of water drainage and its resulting magnitude in situ define a key role here. For example, an experiment with the highly plastic „Gilzum Clay" shows that with a small reduction in the moisture content, approximate 0,15 to 0,3% by water, negative pore moisture tension of approximate 60kPa quickly build up.
Further investigations on undisturbed samples of „Gilzum Clay" with the help of swelling pressure measurements reveal that for a water loss of 1,5%, suction stresses of 250kPa occur (figs. 5, 6).

3.4. *Building loads and his influence on soil deformation mechanisms*

Building sites and other structures transfer additional loads into the subsoil. In doing so, negative pore moisture tensions influence the mechanical behavior of clay soils considerably.

Assuming by saturated conditions (apart from minor air inclusions) in the case of considered clay soils here there exists a binary system. This additional loads are carried by the ground mass and/or pore water. Laboratory experiments show that existing suction tensions are reduced in this situation. The input of additional potential energy is partly compensated by the negative potential. So in this case we are merely witnessing an energy equalization process which, at first, does not lead to deformation effects. Recorded uniaxial deformations are purely elastic and hence can be reserved at will.

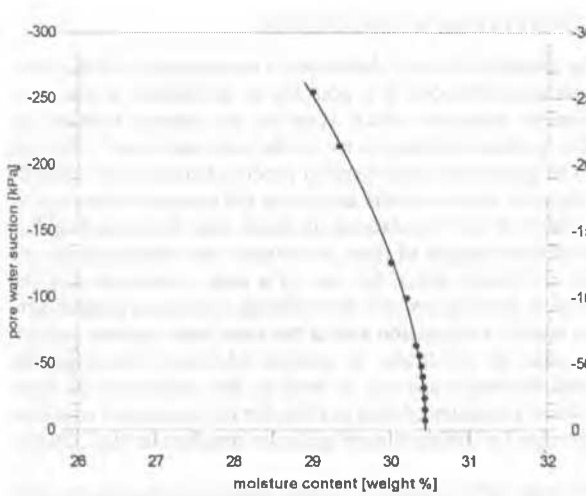

Fig. 6: moisture content in correlation to pore water suction

Only in the case of a complete loss of suction does an excess of pore water pressure build up. At this time the clay releases the pore water until all the forces acting on the pore water are brought into equilibrium.

Loading effects are always connected with a disturbance of the existing pore moisture tension relationships. In a large expanse of solid clay, the effect of a concentrated load is to cause a pore moisture tension gradient which is compensated by a movement of the water. The application of the load always leads to a reduction in the suction tensions and/or the build up of excess pore water pressure. In both cases water is seen to move from the zone of the load application into the adjoining clay.

3.5. *Swelling and shrinkage behavior*

Cyclic swelling and shrinkage trials reveal that the solid clays are obviously resent in a stable condition. Changes to the moisture content and the associated soil deformations can be reserved at will.

These relationships have presumably come about over the course of time as a result of seasonal fluctuations in the climate boundary conditions (cf. Chen 1975). For the buildings affected this means that soil deformations can be expected in the future too; the extent of these merely linked to the local boundary conditions (topsoil, fauna, morphology, climate) and does not result in changes to soil properties.

4. FIELD MEASUREMENT

The influence of the extreme conditions on the behavior of the clay soils and the reaction of the structure affected was observed since 1995 in the area around the historical buildings in Gilzum, Wittmar, Hedeper and Uehrde. The result of the field studies reveal a direct correlation between an increased level of precipitation, the rise in the moisture content of the soil, ground heave and movement of the structure.

Weekly geoelectric measurements since 1995 with an high frequency probe at the „Gilzum Clay", recorded changes in the moisture content at approximate 1 to 2 weight % by water depending on depth. This changes are extremely low. Around the church, the maximum amounts of ground heave are markedly grater than directly adjacent the building itself.

5. SUCTION TENSION AS THE IMPULSE OF SOIL DEFORMATION

The mechanical behavior of the distinctly plastic clay soils of the different locations examined here is determined to a great extend by the interaction of the pore water with the clay soils. During by climate changing's, water is removed from the soils (via evaporation) and shrinkage deformations occur (fig. 7). In the moisture content ranges observed, the soil merely shrinks uniaxially and the volume of the water given up corresponds to the uniaxial change in the volume of the soil. As a result, suction tensions ensue which quickly take on considerable proportions. The provision of water in form of precipitation is adsorbed by the surface of the clay and the existing suction tension reduced until there is no more free water available or the tension is reduced to zero. In both cases the swellings processes are stopped. In the processes described, this is merely an equalization process between differing energy levels in the pore water which are controlled by the provision of free water. Therefore, suction tensions can be permanently present in the distinctly plastic clay soils, depending on the natural surroundings.

Buildings erected on such clay soils hamper the natural evaporation or penetration of precipitation for a section of the clay. Beneath unsealed (i.e. undeveloped) areas periods of dry

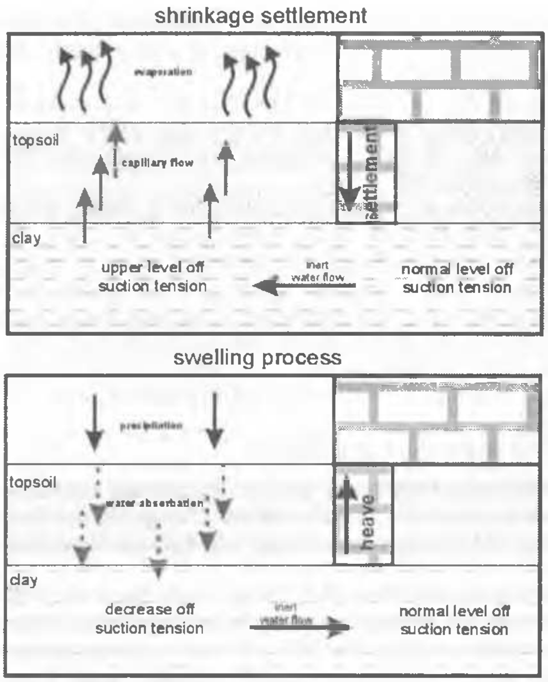

Fig. 7: Mechanics of soil deformation at precipitation and evaporation

weather lead to a rise in the suction tension, while sealed (i.e. developed) areas initially retain their pore moisture tension level. This process creates compensatory movements of the pore water in the direction of the higher suction tensions in connection with an inertia specific to the soil due to the very small cross sections of the pores. As this happens, the outer parts of the building are effected first and the associated shrinkage deformations create an arch profile beneath the building. The tensile stresses which are setup can lead to cracks in masonry, depending on the construction. The soil deformations increase in continual periods of dry weather as we move further away from the building. During subsequent wet weather, the unsealed surfaces of the site first soak up the precipitation. As this happens, the existing suction tension decrease and, again, lateral differences in suction tension build up between sealed and unsealed areas; these are balanced by a slow movement of water (fig. 7).

Water movements also occur upon the application or removal of loads on such soils. The zone effected by the action of the load is extremely small in relation to the extent of the clay soil. In this case the existing suction tensions are reduced in the zone affected by the load. In doing so, a imbalance ensue in the distribution of the suction tension between the zones affected by the load, with correspondingly low suction tensions, and the normally loaded zones, with higher suction tensions. Consequently, pore water must start to move from zones of lower cohesive levels (near the foundations) to zones of higher suction tensions in the course of an equalization process – coupled with settlement of the building.

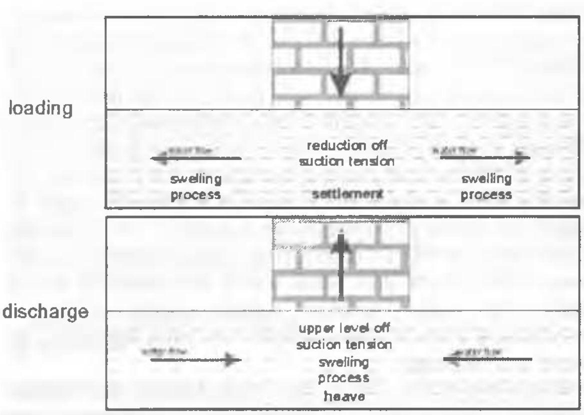

Fig. 8: Mechanics of soil deformation by loading and discharge

Accordingly, in the case of such clay soils with negative pore moisture tensions, settlement under load does not occur as the result of the build - up of excess pore water pressures, and hence the squeezing - out of pore water, but instead is a reaction to variations in the distribution of pore moisture tensions (fig. **8**).

Once these processes are concluded, then the level of pore moisture tension is again in equilibrium across the entire clay soil, depending on the gravity potential. In the case a quasi – infinite layer of clay, this level corresponds to the initial one because the quantity of water from the zones affected by the load is very small in relation to the amount of pore water in the clay soil as a whole. Hence, the level of pore moisture tension in situ does not depend on the load and, in a case of a quasi – infinitive layer of clay with this ability to alter its volume, always corresponds with that of the total system. Consequently, the initial swelling pressures present beneath the building are the same as those in the surrounding areas. Notwithstanding, the extent of swelling and shrinkage is altered by loading because the application of a load and the associated equalization processes of the pore moisture tensions are connected with a change in pore space. The pore space beneath the foundations in diminished. In the course of adding or removing water, pore moisture tension achieve a balanced horizontal distribution, depending on the geodetic elevation. This is only possible through the adsorption or drainage of different amounts of water – related to the size of the pore space. Therefore, in a saturated soil the vertical deformations below the foundations are smaller than those in the adjoining areas.

6. POSSIBLE CAUSES OF INCREASED SOIL DEFORMATIONS

The influence of vegetation, climate changes or the proliferation of drainage systems were all considered as possible causes of increased soil deformations in the areas investigated. The evaluation of climate data for the years 1967 – 1999 and the consideration of various locations in the South – East Lower Saxony (Northern Germany) show that climatic changes and the influence of vegetation are unlikely to be the cause behind increased soil deformations. Many indicators point to extra drainage and hence accelerated dewatering of areas (e.g. due to the installation of sewage or drainage system). The associated faster removal of water shortens the internal water flow before the water drains from the clay. Consequently, in the case of dry weather the onset of soil deformation starts previous. In addition, a resumption of the adsorption of water and a balancing of the existing water deficit becomes more difficult for the soils.

7. REDEVELOPMENT MEASURES

Having identified the soil deformation mechanisms and the natural local circumstances, it is possible to implement in situ – refurbishment measures which stabilise the subsoil beneath the building without needing work to the structure itself. The aim here is to prevent the equalisation process between the different pore moisture tension levels and hence the seasonal influences in the vicinity of the foundations, or keep than from the building for a sufficient length of time. A solution was developed for the church in Gilzum which by way of a non – cohesive soil bed spread over the clay around the building represents reliable protection against evaporation and at the same time enables precipitation water to penetrate. In special laboratory investigations both the shrinkage process as well as the adsorption of water were found velocities of 3cm per day for the horizontal equalization process for different pore moisture tensions in the „Gilzum Clay".

The width of the system is 1,80m, based on knowledge of the velocities specific to the soil for the equalisation process in the pore water. The system will thus withstand a dry-weather phase of 60 days based on the results of laboratory experiments for the „Gilzum Clay".

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