The influence of weathering on the geotechnical properties of Pleistocene coarse grained glaciofluvial deposits in the northern Alpine foreland (Bavaria/Germany)

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ABSTRACT: Weathering has considerable influence on the geotechnical properties of coarse grained Pleistocene glaciofluvial sediments which occur in terraces and plateau-shaped hills in the Alpine foreland around Memmingen (southern Bavaria, Germany). The bedded glaciofluvial gravel of the Hawanger Feld (Field of Hawangen) southeast of Memmingen was investigated in detail; in addition to the shallow soil cover, deep weathering phenomena also occur which manifest as cone or organ-pipe-like structures reaching far down into the apparently unweathered sedimentary body. Dissolution of carbonate grains and disintegration of dolomite (“ashing”) are the major weathering processes which could be detected here. Through both of those processes the proportion of fine sand, silt and clay within these sediments increases. The intention of this study is to characterize weathering processes and to create a conceptual model for the quantitative and qualitative classification of weathered gravel with high carbonate content.

1 INTRODUCTION

Recently primary geological survey and mapping started southeast of Memmingen, within a classical region first investigated by Albrecht Penck (Penck & Brückner 1909). As a result of this work, sheet Nr. 8027 Memmingen will be published, which is part of the official Bavarian geological map in a scale of 1:25 000 (Geologische Karte von Bayern, GK25).

Pleistocene glaciofluvial gravel deposits covering clayey and sandy silts belonging to the Miocene Molasse dominate the area of Memmingen. Originally these carbonaceous meltwater deposits were part of large terminal outwash plains, draining Alpine piedmont glaciers in the south. Today they form mostly even terraces and plateaus at different altitudes, which have different ages and, according to Penck & Brückner (1909), Jerz et al. (1975) or Rögner (2008), can be assigned to different glacial periods (Würm, Riss, Mindel, Günz and Donau). Since their deposition the gravelly outwash plains have been weathered from above, mostly under warmer climatic conditions of Interglacial or Holocene periods. As a rule, older gravel deposits are more affected by weathering than younger ones. Glaciofluvial gravel shows significant shallow and deep weathering phenomena, which can be found within a terrace southeast of Memmingen called Hawanger Feld (Field of Hawangen). This terrace clearly formed before the last glacial period and is assigned to the Riss Glaciation (younger Saale, Illinoian, Waimean).

Near Memmingen, Albrecht Penck (1858–1945), the father of the Quaternary stratigraphy, established his quadripartite subdivision of the Ice Age on the basis of the so called “vier Felder von Memmingen” (“four fields of Memmingen”, see Table 1.) Therefore the area near Memmingen is counted among the important and classic parishes of the Quaternary geology. Penck’s subdivision of the Ice Age in the Alpine foreland had strongly supported other attempts to set up stratigraphic subdivisions of the Quaternary Period in other regions.
of the world. More glacial periods have been added to the original subdivision of the Ice Age established by Penck within the following decades.

Moreover, the Hawanger Feld is a good site to develop a qualitative classification for the weathering of Pleistocene carbonaceous glaciofluvial gravel deposits. Until now a classification system for the weathering of gravel has not been available. The present study will try to establish a basis for a classification system for weathered gravel.

2 GEOGRAPHIC AND GEOLOGICAL OVERVIEW

Memmingen (599 m above sea level) is a small town located in the district of Unterallgäu in south-western Bavaria (Germany) at the northern Alpine foreland, about 100 km west of Munich and 40 km north of the Alps. The hilly landscape is characterized by S-N-orientated valleys accompanied by terraces, knoll ridges and plateaus. The valley floors, terraces and plateaus are made up of Pleistocene gravel, covering Miocene freshwater sediments belonging to the Upper Freshwater Molasse which are exposed at many hillsides. The Pleistocene sediments have been formed by meltwater deriving from large Alpine glacier lobes in the south, belonging to the Iller and the Wertach-Lech Piedmont Glaciers. The source area of these glaciers is situated within the Allgaeu, Ammergeau and Lechtal Alps, which are mostly parts of the Austroalpine unit (Northern Calcareous Alps). These piedmont glaciers had different extensions in different glacial periods, but varying widely as well within a single glacial period. Different from other sites in the Alpine foreland these glaciers attained their maximum extension in the Mindel Period, which may be an equivalent of the older Saale or Kansan glacial period. In the opinion of Jerz et al. (1975) it is possible to distinguish four different levels of terraces within the study area, former glacial outwash plains that can be assigned to glacial periods: Günz, Mindel, Riss and Würm. However, according to Rögner (2008) deposits of the Günz Glaciation are missing here. Depending on their different ages most of the glaciofluvial gravels are either more or less intensively weathered and/or more or less solidified by calcareous cements.

3 GLACIOFLUVIAL GRAVEL DEPOSITS OF THE HAWANGER FELD (RISSIAN)

3.1 Stratigraphy and Genesis

The Hawanger Feld is located 2 km east of Memmingen forming a terrace of Pleistocene glaciofluvial gravel deposits 30 m above the valley floor of today. The highly carbonaceous gravel exposed here has a thickness of 13 to 18 m, covering much older clayey to sandy siltstones of the Upper Freshwater Molasse. The upper 2 to 2.5 m of the gravelly deposits have a brown color, are highly to extremely weathered and mostly decalcified. This soil is overlain by partly decalcified, loamy loess which is two to several meters thick (see Figure 1).

The gravel of the Hawangen Feld has originally been deposited by meltwater derived from the Iller Piedmont Glacier on an outwash plain. This Alpine glacier came from the Iller
valley within the Allgaeu Alps. During its maximum expansion in the Riss glacial period the Iller Piedmont Glacier covered the southern part of the Alpine foreland and advanced until Bad Grönenbach, situated only 10 km south of the study area. Thus, the Hawanger Feld has never been covered with glacier ice.

3.2 Petrography and geotechnical properties

The non-weathered glaciofluvial gravel consists of a mixture of coarse grained gravel (grant) and sand with highly variable proportion of fine grained matter (clay and silt) and cobble. Single blocks occur here and there. The deposits show distinctive, nearly horizontal bedding, some of these layers are cross bedded. Regarding grading and grain size every layer is different. Locally well graded sand layers or layers consisting of a blend of sand and grant can be found to overlie well graded grant layers. Due to the source area of the Iller Piedmont Glacier mostly situated within the Northern Calcareous Alps and the Helvetian Mountains, the gravel contains at least 80% carbonate pebbles, mostly Mesozoic fine-grained limestone and dolomite. In contrast, only around 1 to 2% of the pebbles are crystalline or quartz grains. The natural compactness of the packing is high and therefore also the load-bearing capability and stability. Accordingly the compactability of the gravel is low. Because of the primarily low content of clay and silt the gravel has a low susceptibility to frost, a low incidence of mass movements, a low water content and capillarity, shows a good soil permeability as well as reusability. Shortly summarized: Non-weathered glaciofluvial gravel is an excellent building ground and an outstanding good material for all kinds of earthwork.

3.3 Weathering of the glaciofluvial gravel

Currently, the gravel of the Hawanger Feld is mined in a large gravel pit near Hawangen village. At the faces of that gravel pit, both shallow and deep weathering phenomena can be studied (see Figure 2).

The surfaces of Würmian and pre-Würmian gravel bodies are affected by wide spread and relatively shallow weathering, leading to the formation of decalcified and brown soils, which grow
thicker and thicker with increasing age of the terraces. However, in the Memmingen area deep local weathering phenomena also occur. They are restricted to small areas with diameters of about 1 m, reaching far downwards into the seemingly unweathered sedimentary body. They appear as brown and decalcified cone or organ-pipe-like structures, occurring in non cemented loose gravel as well as in strongly cemented conglomerates. Field and laboratory investigations regarding the processes and products of shallow and deep weathering have been carried out here. Based on these investigations a preliminary concept for a qualitative classification for weathered Pleistocene highly carbonaceous gravel has been worked out and is presented here (see Section 4).

After the meltwater gravel of the Hawanger Feld had been deposited within an outwash plain under cold climatic conditions, the weathering of the gravel body began most likely under warmer climatic conditions of the Eem-Interglacial (Sangamonian, Oturian). Subsequently, the soil formation must have been interrupted for a long time during the Würm Glacial (Weichsel, Wisconsin). Presumably it started again in the Interstadials of the Late Würm, continuing through Holocene until today.

The weathering must have started at the terrace surface, the weathering front moving slowly downwards into the ground. Infiltrating precipitation water connected with humic acids may have controlled this process. The color change from grey to reddish-brown is normally considered to be the main weathering front and coincides with the border between high and low in carbonate content. However, own investigations show, that even below this borderline, which is clearly visible in the outcrops weathering has already occurred. The color change strictly marks only the border between slightly and moderately weathered gravel at the bottom to highly and extremely weathered gravel at the top. From this more or less horizontally orientated interface the weathering of the material reaches far down into the gravel such that there really is no fresh material in the gravel pit of Hawangen! In the same outcrop brownish cone or organ-pipe-like structures, which are the products of deep, punctual weathering, also occur. According to Penck & Brückner (1909) they are called “geologische Orgeln”. The pipes are vertically oriented, circular tubes with diameters of 0.3 to 1.0 m, surrounded by light-colored seemingly not weathered gravel. The gravel is penetrated by the structures from above at least a couple of meters below the interface mentioned above. Many pipes are 4 to 5 m or even more than 7 m deep. The diameter of the structures remains constant with only small convexity and constriction. The shape of the tubes seems to be not influenced by the bedding and inhomogeneities of the gravel. In the upper parts the pipes are filled with rather isotropic reddish-brown,
loamy, highly to extremely weathered gravel showing no signs of bedding. The lower parts of the tubes are filled with grey to pale brown, slightly to moderately weathered, gravel which shows bedding similar to the surrounding gravel. However, the brown tube fill is comparably loose and shows clear structures of settling (see Figure 2). The vertical interface between the pipe fill and the surrounding gravel is distinct. Everywhere in the gravel-pit wall many parallel “organ-pipes” can be observed, at distances of 3 to 4 m and sometimes of only 1 to 2 m. In places they are so closely spaced that they are overlapping with each other (see Figure 3).

Why and how do these pipes develop? Previous investigators (Penck & Brückner 1909, Jerz et al. 1975, Jerz 1993 and Scholz 1995) of similar structures had different ideas for their formation. Some were interpreted as (a) sedimentary structures within the gravel formation, (b) ice-wedges, (c) fissures caused by differences in the settlement of the sediments or (d) channels of raised water permeability as a result of interior relocation processes. However, setting together all results of the field investigations there can be only one conclusion: The formation of these organ-pipe-like structures begins at the surface of the gravel formation and develops downwards. Most likely their formation is induced by a surface inhomogeneity within the soil. Patterned ground could be the reason which is typical for periglacial areas. In fact, at many sites in the area between Memmingen and Kaufbeuren-Neugablonz a sorting is visible in soils, which can only be interpreted as patterned ground. These cold-climate structures could be the priming for the weathering in the following warmer period and in the aftermath the weathering evolves into a self-preserving and self-energizing process. The weathering of the gravel causes also the beginning of changes of the geotechnical properties.

3.4 Weathering processes and their influence to the geotechnical properties

Because of the extremely high content of carbonaceous pebbles and sand grains in the gravel of the study area (see above) several weathering phenomena are common: decalcification and associated browning, disintegration of dolomitic components, acidification and an increase of the clay content.

Figure 3. A ramp in the gravel pit near Hawangen is cutting densely spaced “organ-pipes” (geologische Orgel), showing the distribution of the pipes within the gravel formation (scale is a 5 liter bucket).
3.4.1 Decalcification
Decalcification is the main weathering process and affects all grains with carbonate content like limestone, dolomite marlstone or carbonate cemented sandstone and other clastic sediments. The carbonate dissolves and insoluble substances like clay, silt and quartz grains are freed. Thus the proportion of the fine-grained content in the gravel increases and the porosity of the gravel is reduced. Chert and quartz grains are particularly insoluble. Due to the accumulation of these hard mineral grains the abrasive character of the deposits increases. The decalcification starts at the surface of the pebbles proceeding gradually towards the center of the grains (see Figure 4). As a considerable proportion of the grant grains disappear due to solution the grain size distribution changes extensively together with the geotechnical properties of the gravel. Browning and acidification are secondary effects of the decalcification and enforce the weathering. Browning is an effect of the formation of ferrous oxides and hydroxides, which is an evidence of the (nearly) completed decalcification of the weathered gravel (Blume et al. 2010). The pH-value falls below 7.

3.4.2 Disintegration and “ashing” of dolomite
Disintegration and “ashing” is the second major weathering process, affecting mostly dolomitic pebbles and sand grains. Prior to the carbonate solution, weathering processes lead to a disintegration of the dolomite crystals and to the transformation of stable grains into soft dolomite crystal sand and silt, called “dolomite ash”. In this way the share of fine-grained matter increases within the gravel, too. The “dolomite ash” as well as the fine grained matter deriving from decalcification can be dislocated by percolating rain water or flowing ground water within the gravel body and redeposit somewhere else in the gravel formation. Caused

Figure 4. Petrographic thin section of a siliceous limestone from the Penninic Flysch Zone (5x magnified, transmitted light, crossed nicols, width of the image section 2.5 mm); the front of decalcification divides the image axial. The right side shows the nearly unweathered limestone with carbonate (grey matrix); the left side shows the nearly complete decalcificated limestone; the siliceous material forms a stable framework and instead of the carbonate are pores that appear black in the thin section.
by redeposition of fine-grained matter pores could be closed which affects and lowers the porosity of the whole rock.

3.4.3 Cementation
Cementation is not a weathering process in the narrow sense of the term. However the cementation is certainly supported by weathering processes at the surface, which enrich the percolating rain water with carbonate. The carbonate dissolved below the surface can cause a selective or extensive cementation deeper within the gravel body due to the precipitation of the calcite along the grain contacts of sediment layers.

4 CONCEPT OF A QUALITATIVE CLASSIFICATION FOR WEATHERING OF PLEISTOCENE HIGH IN CARBONATE GLACIOFLUVIAL GRAVEL DEPOSITS

After analyzing all the results of the previous field investigations and the first results of the laboratory investigations it is possible to establish a preliminary concept of a qualitative classification for the weathering of Pleistocene glaciofluvial gravel rich in carbonate (see Table 2). The classification proposed here is according to the commendations of the ISRM (1978) and the IAEG (1981) and to the descriptions given by Spaun & Thuro (2000) concerning the weathering of hard rock.

During succeeding field and laboratory investigations this concept will be checked and modified in order to establish a classification system for weathered gravels in the future.

### Table 2. Concept of a qualitative classification for weathering of Pleistocene glaciofluvial gravelly deposits with high contents of carbonate clasts (Lempe in prep.); W = weathering grade, V = weathering class.

<table>
<thead>
<tr>
<th>W</th>
<th>IAEG-ISRM</th>
<th>V</th>
<th>Description of the weathering according to Lempe (in prep.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Fresh</td>
<td>1(gravel)</td>
<td>The grains show no alteration; nearly all grains with smooth surfaces.</td>
</tr>
<tr>
<td>II</td>
<td>Slightly</td>
<td>2(gravel)</td>
<td>Certain grains* show weak changes in color and rough surfaces.</td>
</tr>
<tr>
<td>II–III</td>
<td>Slightly to moderately</td>
<td>3(gravel)</td>
<td>Many grains* show weak changes in color and rough surfaces. Certain grains (mostly dolomites) show a thin cortex with sponge-like porosity respectively with signs of disintegration (“ashing”); some dolomites are already disintegrated.</td>
</tr>
<tr>
<td>III</td>
<td>Moderately</td>
<td>4(gravel)</td>
<td>Many grains* show a distinct change in color, mostly dolomites show a cortex with sponge-like porosity respectively with signs of disintegration (“ashing”). Many dolomites are disintegrated (“ashed”). Noticeably increased clay content of the gravel, weak to remarkable loss of volume/mass.</td>
</tr>
<tr>
<td>IV</td>
<td>Highly</td>
<td>5(soil)</td>
<td>Nearly all grains* show a distinct change in color and a sponge-like porous cortex. Nearly all dolomites are disintegrated (“ashed”), limestones mostly to dissolved completely. Distinctly increased clay content, distinct loss of volume/mass; browning of the soil starts.</td>
</tr>
<tr>
<td>V</td>
<td>Extremely</td>
<td>6(soil)</td>
<td>Nearly a complete change of color of the whole soil. Dolomite and limestone are missing. Strongly increased clay content, strong loss of volume/mass; distinct browning of the soil.</td>
</tr>
<tr>
<td>VI</td>
<td>Residual soil</td>
<td>7(soil)</td>
<td>The fine-grained matter of the weathered gravel is mostly or completely washed away, only chips and fragments of the weathering-resistant grains left over (“Restschotter”); complete and strong browning of the soil.</td>
</tr>
</tbody>
</table>

* siliceous limestone, dolomite, marlstone, sandstone etc.
5 CONCLUSION

Due to the weathering processes a non-cohesive soil gradually turns into a cohesive soil. Weathering-resistant materials, which include quartz, igneous and metamorphic siliceous grains, siliceous cement and chert, accumulate in the deposits which results also in an increase of the abrasive character of the deposits. The dissolution of carbonaceous materials (non cemented rocks may also karstify!) causes a significant loss of material/volume and is resulting in settlements or large area subsidence of the ground surface.

Another phenomenon of the dissolution of carbonates below the ground surface is the subsequent precipitation of the carbonates along the grain contacts of sedimentary layers deeper in the gravel body, which results in a selective or extensive cementation of the rock. In this way, originally loose, non-cemented gravel is grading into a solid deposit (conglomerate).

The type of soil, compactness of the packing, frost-susceptibility, capillarity and compactability, porosity and soil permeability, re-usability, settling properties, weathering-potential, susceptibility to erosion, preference for mass movements are important properties of the soil for both, earthwork in and usability of the gravel. During the process of weathering these properties vary in wide limits.

Therefore it is important and essential to investigate and to describe very accurately the weathering status of the ground in course of any phase of the survey for earthworks and building projects.

REFERENCES


