The geology of Munich (Germany) and its significance for ground modelling in urban areas.

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Abstract: The city of Munich forms the core of a fast growing urban region in the Alpine foreland of Bavaria, in southern Germany. The subsurface is composed of Neogene and Quaternary formations made up of loose alluvial, fine- to coarse-grained sediments. Today's landscape is known as the Munich gravel plain, which comprises sander terraces formed during the Pleistocene glacial periods as well as the modern floodplain of the river Isar. Caused by a major unconformity and hiatus, these rather young gravel terraces overlie Neogene Molasse deposits of the Alpine foreland basin, which in contrast comprise of fine-grained fluviatile and lacustrine facies.

The geology of Munich is well known due to numerous underground structures (e.g. subway tunnels), which were built in the past decades. Nevertheless, the multiphase geological history and the complex sedimentary architecture in combination with new construction methods constantly raises new geotechnical problems and challenges. Requirements for geological site investigation and ground modelling thus are very high as it is the case in many other urban areas worldwide, which face similar ground conditions, e.g. cities in major floodplains, coastal areas or forelands of mountain belts.

This paper tackles the major aspects of ground modelling in Munich and gives insight into the interplay of geological history and geotechnical requirements. In detail, the engineering geological significance of the model data will be outlined, including the structure of fluviatile sequences, erosive and weathering processes, petrographic composition, early diagenesis, the formation of joints and slickensides as well as the complex hydrogeology. By means of examples, the increasing need for comprehensive ground models that summarize the totality of the geological history will become evident.

Résumé: Munich est le centre d'une agglomération urbaine située en Bavière au pied des Alpes. Le sous-sol est composé de sédiments alluviaux meubles datant du Néogène et du Quarternaire. En raison de nombreuses mesures de construction de tunnels et de travaux publics en sous-sol, il existe d'une part une connaissance détaillée de la Géologie de Munich. D'autre part, l'histoire et la structure géologiques complexes donnent régulièrement lieu à de nouveaux problèmes et défis géotechniques. L'exploration géologique est de ce fait soumise à de hautes exigences, comme c'est également le ces dans de nombreuses autres grandes villes, situées dans un environnement géologique comparable.

Cet article est consacré aux aspects principaux du modelage du terrain à bâtir à Munich et donne un aperçu de l'interaction entre les processus géologiques et les conséquences géotechniques actuelles.

Keywords: Geology of cities, rivers and streams, engineering geology, substructures, site investigation.

INTRODUCTION

The geology of Munich is dominated by loose sediments, like gravels, sands and clays, which accumulated in continental environments over the past 15 million years. Deposition took place in fluvial as well as glacial sedimentary settings. Floodplains, alluvial fans and glacial sander terraces were formed by and subjected to repeated phases of weathering and erosion. The geology of Munich is explored to a high degree which is due to the civil engineering works of the last decades, like subway or car tunnels (e.g. Gebhardt 1968). The experience, however, shows that anticipation and understanding of the complex ground conditions still require specific geological investigation strategies and detailed ground models for each site.

Comprehensive geological ground models, in general, encompass the rock forming processes and environments, but also later modifications by diagenesis or tectonics and morphological processes (total geological history, Fookes et al. 2000). The subsurface of Munich offers a valuable case study of urban geology and its demands on ground modelling. In the following, we will briefly outline the total geological history of Munich during the Neogene and Quaternary and give key examples to explain its impact on engineering geology and its consequences for geotechnical engineering.

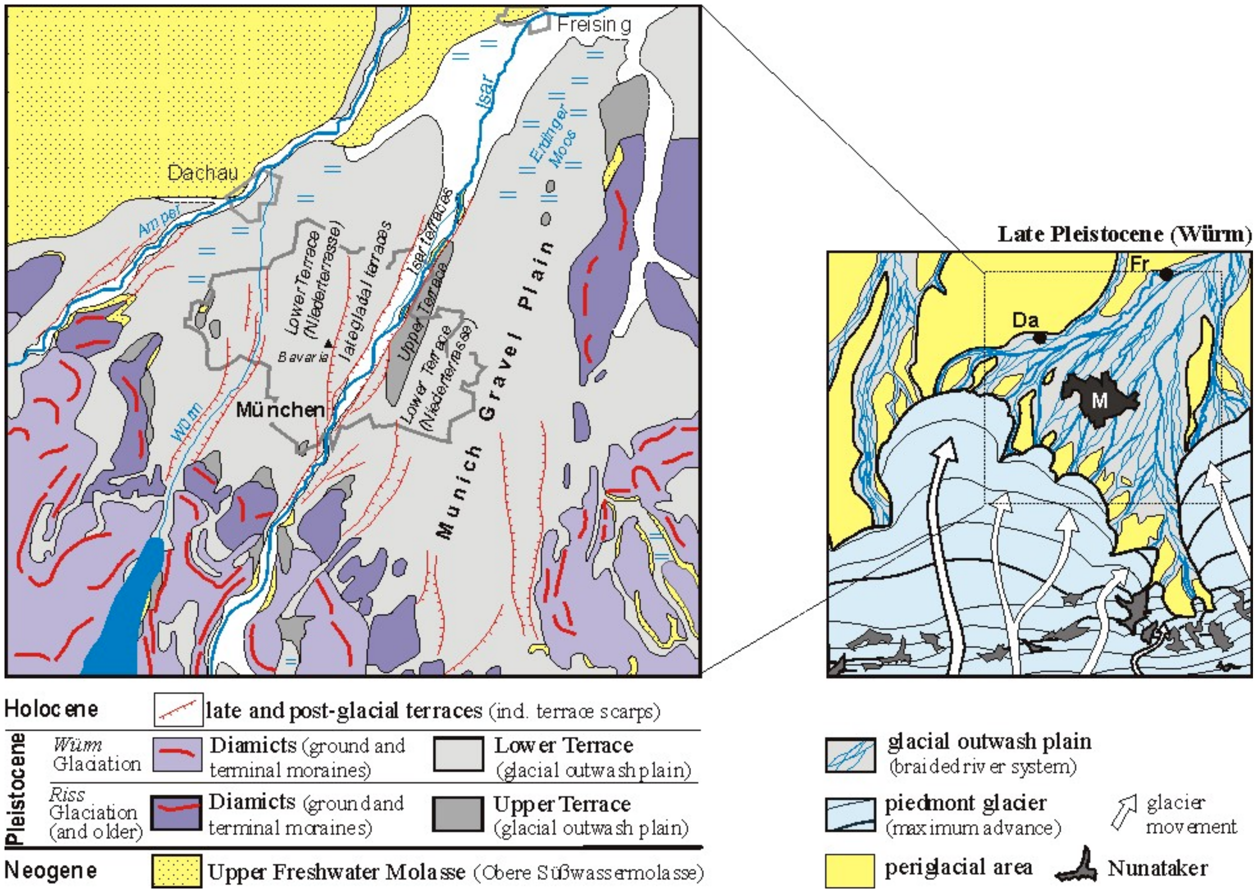

Figure 1. Simplified geology of the wider Munich area. Map to the right shows the paleogeographic situation in the late Würm glacial period roughly 25.000 years ago (after Tillmann 1953, Unger et al. 1991 and BGLA 1996).

GEOLOGICAL STRUCTURE AND EVOLUTION

Munich is situated in the northern foreland of the Alps in Bavaria (Figure 1). The geological evolution was controlled by foreland basin deposition (molasse) in the course of Tertiary Alpidic orogeny (Lemcke 1998) and by the Pleistocene glaciations. The subsurface of Munich, at least the part affected by underground structures, is thus composed of two major lithostratigraphic units (Figure 2). The Munich gravel plain consists of Quaternary (mainly Late Pleistocene) glaciofluvial gravel terraces of up to some tens of metres in combined thickness. With a major unconformity, these gravel deposits cover Neogene sediments of the Upper Freshwater Molasse (Obere Süßwassermolasse), which is the upper part of the up to several km thick filling of the Bavarian Molasse Basin. The encountered Molasse deposits are comparatively fine-grained and of fluvial and lacustrine origin. The general stratigraphy is displayed in Figure 2.

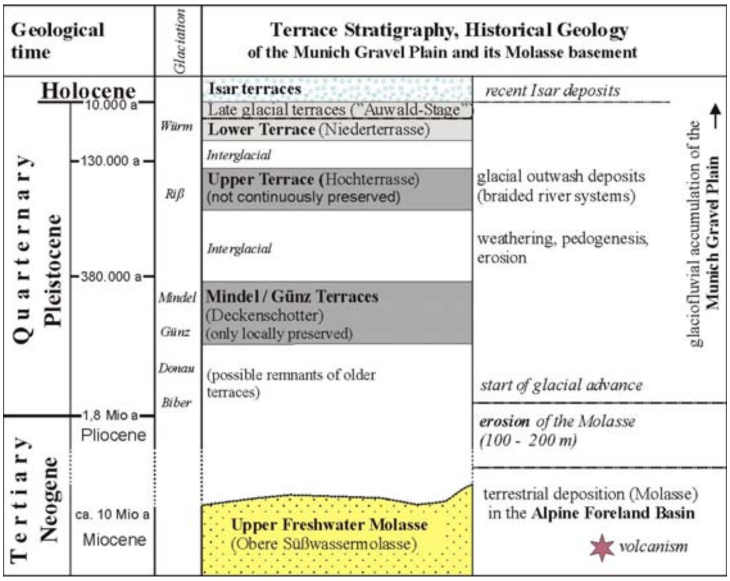

Figure 2. Stratigraphy in Munich

In the following, the earth history will be outlined separately for the Neogene and Quaternary periods. We will define the sedimentary environments, the composition and spatial relationships of the deposits and discuss their subsequent modifications due to compaction, early diagenesis, weathering and erosion.

Molasse deposits (Neogene)

Paleogeography and -environment

During the Palaeogene and Neogene, the North Alpine Molasse Basin (foreland basin) developed in response to the advance and rise of the Alpidic mountain belt. Subsidence was accomplished by rapid sediment accumulation in alternating marine and terrestrial environments. The bulk of sediment, which reaches from clay to gravel, was derived from erosion of the uprising Alps in the south. In the Neogene warm humid climate conditions prevailed and a extensive terrestrial basin with meandering rivers and associated lakes and marshes developed (Upper Freshwater Molasse). Clastic material was transported and deposited in alluvial fans and river channels (point bars) and as overbank deposits on the floodplains. In Pliocene times deposition ceased and erosion of up to 200 m of sediment in the area of Munich took place lasting into the Pleistocene.

Sedimentary structure and composition

Main constituents of the Molasse in the subsurface of Munich are brown, green and blue clays, silts and marls as well as mica-rich sands and, locally, gravels and sandy gravels rich in quartz and crystalline detritus. The complex three-dimensional fluvial geometry is characterized by sandy and gravely lenses and beds that originated as point bar sequences in migrating river channels. These coarse sediments were deposited as bedload and display typical sedimentary structures like ripple cross-lamination and cross-bedding. With sharp erosive bases these channels are intercalated into fine-grained soils that were deposited on the river embankments, as overbank deposits (e.g. during flash floods) and levees. Characteristic features like fine lamination and drying cracks can be observed.

Locally, clayey sediment of volcanogenic origin can be intercalated into the fluvial sequence. These bentonites were derived from the decay of volcanic ashes (e.g. Unger, Fiest & Niemeyer 1990, Ulbig 1994).

Post-depositional processes

The Molasse sediments were affected by early diagenetic processes. Due to burial and overburden pressure of up to 200 m of sediment, that was later removed by erosion, the deposits of the Molasse are highly compacted and overconsolidated. Cohesive soils are hard and firm, granular soils exhibit high compactness. Locally, lithification and cementation took place leading to the formation of nodules or even beds of hard rocks like marlstones and sandstones. Compaction and lithification often is accompanied by fracturing and the formation of regular joint systems. Friable clays and marls occur that are characterized by microfissures and small-scale slickensides.

Glacial and post-glacial gravel deposits (Quaternary)

Paleogeography and -environment

In the Pliocene, the climate entered a cooler phase with pronounced cyclic changes leading to multiple glaciations in the Pleistocene. The Munich gravel plain represents the pro-glacial lowland in front of the alpine glaciers, in which coarse debris (glacial outwash) accumulated episodically. These glacio-fluvial sediments commonly display the same characteristics as deposits of braided streams.

Based on the pioneering work of Penck & Brückner (1909) a sequence of gravel terraces can be recognized (Figure 1), which reflects phases of deposition, probably during the climax of each glaciation. These phases alternated with episodes of weathering during intergalcials with the formation of paleosols and intense fluvial incision and erosion during waxing phases of glaciations. Due to these cyclic processes the substratum was repeatedly eroded and levelled. The youngest glacial terrace (Lower Terrace) is most widely preserved and rests unconformably on Neogene Molasse deposits and remnants of older terraces. The Molasse surface is incised by channels and gorges. Locally, the Molasse and the older terraces protrude as islands within the Lower Terrace.

Sedimentary structure and composition

The gravel terraces can reach individual thicknesses ranging between a\ few meters and 20 m. Each terrace is composed of lens-shaped or tabular sedimentary units. The main sedimentological feature of these units are horizontally stratified, imbricate gravels as well as planar cross-stratified gravels. Deposition took place in bars and in migrating channels of the braided outwash plain. A variety of typical gravel facies can be subdivided depending on gradation (e.g. openwork gravels, matrix-rich gravels) and composition. Main constituents are carbonate gravels derived from the Northern Calcareous Alps, but episodically (Riss glaciation) deposition of crystalline-rich debris occured. Layers of sand and silt resembling floodplain deposits are generally subordinate. Due to age and modifications from multiple glaciations and interglacials the degree of compaction, weathering and lithification generally decreases from the older to the younger terraces.

Post-glacial processes

At the end of the Pleistocene the modern river Isar established itself. In the south of Munich, the Isar valley has the shape of a canyon, whereas in the north it becomes wide and a number of fluvial Holocene terraces can be subdivided. Due to generally high groundwater levels in this northern area of the Pleistocene gravel plain, lower-moor peat and bog lime (tufa) are widespread.

HYDROGEOLOGY

The subsurface of Munich represents a multiple aquifer system that is closely related to the lithostratigraphy. Basically, an upper rather homogeneous aquifer is situated within the Quaternary gravel deposits which must be distinguished from groundwater occurring in granular soils of the Neogene Molasse (Figure 3). The breweries of Munich extract groundwater from the Molasse in depths of more than 150 m. Furthermore, karstic groundwater occur s in Jurassic limestones that underlay the Molasse in more than 2 km depth. Locally, geothermal energy is produced.

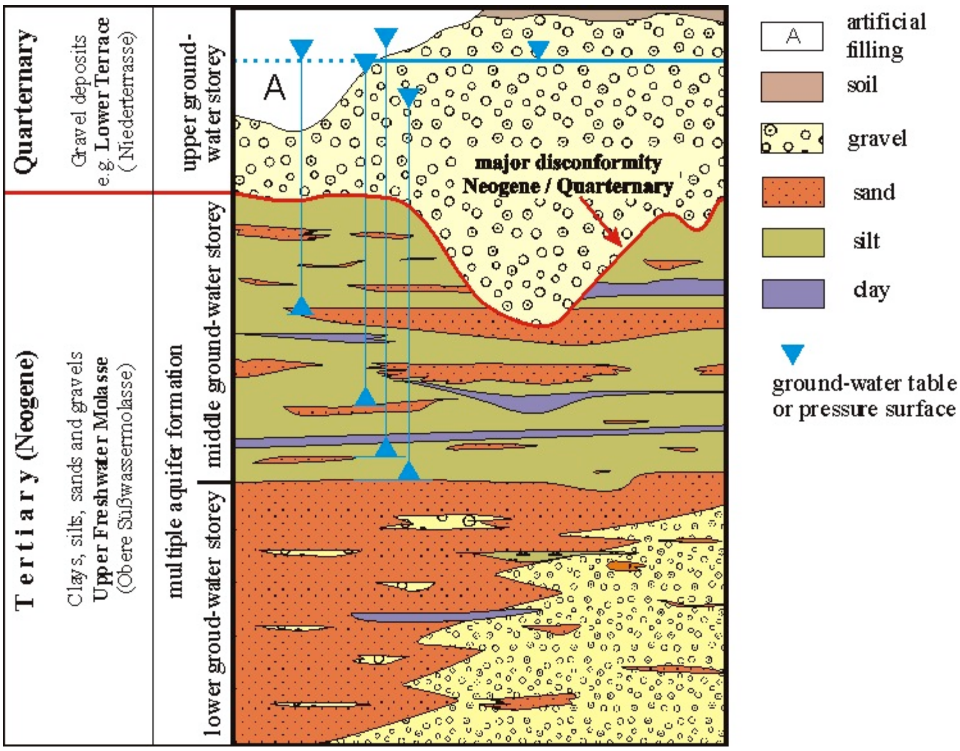

Figure 3. Simplified sketch of the alluvial ground of Munich and its hydrogeology

Quaternary ground-water storeys

The coarse sediments of the gravel plain act as a homogeneous aquifer. The groundwater flow direction is to the north and northeast with the Isar acting as a receiving stream. The gravel plain is wedge-shaped and thins out to the north leading to groundwater outcrops and the subsequent formation of peat and bog lime in this region of the plain.

In the last decades a general recession of the ground-water level can be observed in the wider area. Due to the construction of a major storage reservoir in the upper course, the Isar lacks bedload with the effect of increasing fluvial incision downstream.

Tertiary ground-water storeys

The hydrogeology of the Molasse, in contrast, is rather complex. The fluvial architecture is responsible for the occurrence of numerous aquiferous layers and lenses composed of gravel, sand and sometimes even silt, that are intercalated with impermeable deposits. Due to the un-conformable contact between the Molasse and the Quaternary, hydraulic windows lead to local connections to the overlying Quaternary aquifer. Artesian groundwater flows are therefore a common occurrence.

ENGINEERING GEOLOGY

Based on the total geological history, which was summarized above, some selected major engineering geological and geotechnical phenomena will be outlined as key examples.

Coarse grained soils

Granular soils like Pleistocene or older gravels as well as sandy deposits vary in properties such as composition, fabric, sedimentary structure, lithification or density. In specific, site evaluation has to regard the following phenomena, which strongly influence geotechnical behaviour, like excavability, and planning of e.g. excavation, support measures or foundation.

Nagelfluh

The oldest gravel terraces are affected by lithification. The degree of cementation by calcite ranges from weakly cemented gravels to hard and solid conglomerate, which is called Nagelfluh. Cementation can be patchwork-like and thus create very hetereogeneous ground.

Openwork gravels

Very well graded gravels are a common facies in the glaciofluvial and fluvial systems. These deposits lack sand and fine-grained cohesive constituents, which have been washed out. Openwork gravels are non-cohesive and highly permeable for groundwater as well as injection emulsions. The occurrence of such gravels is important for the assessment of slope stabilities or for the planning of injection measures.

Weathering and decomposed dolomite gravels

In the older gravel terraces the degree of weathering is high. Loosening and decomposition into fine-grained cohesive soils can be observed. Locally, loose sandy pipe-like structures appear within solid conglomerates. Decomposition is especially apparent in dolomite gravels. These are typical components derived from Triassic formations of the Alps. They decompose rapidly keeping their shape, but completely losing their strength.

Abrasiveness

In contrast to the Quaternary sediments, the Neogene gravels are almost exclusively composed of quartz and crystalline debris. Abrasiveness is thus high and has to be taken into account planning excavation measures.

Fine grained soils

The soil mechanical properties of clays, silts and cohesive fine sands in the subsurface of Munich vary strongly. The fine-grained soils encountered are overconsolidated and, generally, hard and firm, but can change rapidly into soft soils by weathering and loosening. A broad range of geotechnical facies occur.

Friable clays

Special attention needs to be paid to frequently occurring friable clays and marls. The microfissures and small-scale slickensides influence soil mechanical properties, like friction angle, cohesion or permeability.

Aquiferous silts

Silt lenses can contain artesian groundwater. Due to the fine-grained structure water drainage is difficult, sometimes even impossible, causing slope stability problems or ground failure.

Bentonitic clays

Bentonites are formed mainly from smectitic clays as an alteration products of volcanic ashes. Smectite-rich layers can be observed in the Neogene sequence in the subcrop of Munich. These layers contain swellable clays and are characterized by low friction angles.

Disconformities

Disconformities of different scales and hierarchical orders are a main stratigraphical feature of the ground in Munich. As mentioned, the predominant disconformity is the boundary between the Neogene and Quaternary deposits, which resembles a paleorelief that formed over a time period of some millions of years. Disconformities of lower hierarchical orders are represented by the bases of fluvial and glaciofluvial erosive channels. Disconformities are of high geotechnical and hydrogeological significance since they can represent for example hydraulic windows or cause problems in the embedding of sealing walls due to a pronounced erosive relief. High-resolution three-dimensional preliminary investigation of the Quaternary-Neogene boundary is thus essential for geotechnical planning and construction.

Figure 4. Holocene fluvial gravel channel incised into Neogene finegrained soils. Slope of excavation pit north of Munich (slope is 4 m high)

Landslides

In the south of Munich, incision of the Isar formed a canyon that exposes a sequence of glacial terraces and fine-grained Neogene sediments at its base. The older terraces are lithified forming steep embankments. Depending on the mechanical properties of the soils and the structure of the slopes, a variety of large- to small-scale landslide phenomena can be observed. These range from creep of conglomerate boulders and rockfalls to translational failures along weak clay layers in the Molasse as well as rotational slides.

CONCLUSIONS

As many urban areas worldwide, Munich is situated in a rather young sedimentary environment, in which loose sediments have accumulated as described in this article. The geological history is characterized by the interplay of fluvial and glaciofluvial deposition, burial and diagenesis on the one hand and landforming processes like weathering and erosion on the other. As a consequence, the ground and hydrogeological conditions are rather heterogeneous. The soils, as shown, are irregularly arranged and highly variable in their properties. These conditions raise a broad variety of geotechnical problems, which challenge geologists and civil engineers at the same time. From desk studies to the in-service stage sound site evaluation and the development of accurate ground models, that take into account the total geological history of a site, remain the precondition for successful and economic design and construction.

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