Foundation Improvement of historic buildings by micro piles, Museum Island, Berlin and St. Kolumba, Cologne

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ABSTRACT

The conservation of historic buildings for future generations is of great importance. Damage is frequently caused by the foundations no longer being able to transfer structural loads without the occurrence of settlement. In such cases micro piles are often employed for rehabilitation of the foundation. Two examples, the Museum Island in Berlin and St. Kolumba in Cologne, have been taken to demonstrate the great flexibility and wide scope of utilization of this method.

1. Introduction

The necessity for foundation improvements is a result of foundations in historic buildings being inadequate mainly due to ignorance of the foundation soil properties when the building was erected.
A further need for the execution of such foundations arises when load increases occur owing to the building being used for a purpose other than that originally planned. With respect to the rehabilitation of old buildings, there is frequently excessive stress on the existing foundations resulting from an increase in the structural and imposed loads. The original foundation is no longer strong enough for the transfer of additional loads so that stabilization measures are required.
At times, a complete renewal and replacement of an already existant deep foundation is called for. This is often the case when present timber piled foundations rot away as a result of water level fluctuations and changed conditions in the immediate surroundings.
For the above-mentioned areas of application, the use of micro piles offers an ideal solution. Micro piles can also serve the purpose when there is only a limited opportunity for using grouting systems because of the types of soil met (e.g. organic soft strata). Furthermore, when employing methods such as jet gouting the existing piled foundations can cause problems during operations if shadow formation cannot be ruled out. In the case of heavily loaded single columns with small cross section dimensions, pile underpinning is often the only way to tackle the job.
The special solutions mentioned here are described in more detail on the basis of a few practical examples.

2. Micro Pile as Foundation Improvement Element

2.1 Manufacture and Pile Systems

The pile systems discussed here are exclusively skin friction piles to DIN 4128, which, owing to their minimal settlement, are highly suitable for the construction tasks to be carried out. Various types of micro piles are employed such as the

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Stump-system steel-tube pile, the Stump-system composite pile, or the reinforced small-bore grouted pile. The pile types are given in Fig. 1.

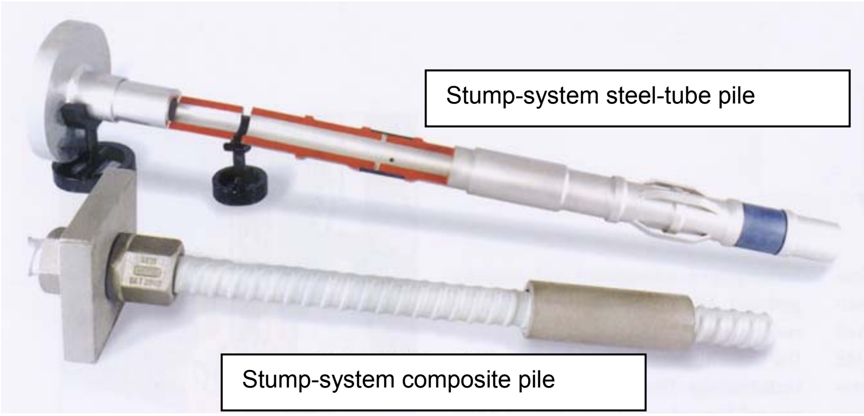

Fig 1: micropile systems

The optimal suitability of the skin friction piles in respect to their load-bearing and deformation properties has been confirmed in comparative large-scale tests with various pile systems [1].
In almost all cases the space available for the foundation improvement operations is very limited. Quite often the work has to be carried out in basements with room heights of not more than 2 m. The basement drilling gear used today is adapted to these conditions. It can be transported to the drilling location under conditions where the space available is extremely limited, to be erected right there.
Borehole diameters mainly depend on both pile system used and soil conditions. Pile diameters most frequently used vary between 100 and 300 mm. The drillings are sunk using the twin-point drilling method and the flushing medium used is water, suspension or air. With this drilling method all soil types and existing obstacles can be worked through without causing damage to the existing building structure. This permits drillings in timber-pile founded buildings, even by possibly drilling through individual piles.
After the drilling has been sunk the steel load-bearing member or reinforcing cage is installed. In cases where the working height is limited, it will be necessary to install various short, sleeve-connected sections. The load-bearing members are joined in compliance with building supervisory authority requirements, or applicable standards. After the steel load-bearing member or reinforcement has been installed, the bore hole is filled with cement suspension or a bore pile concrete of small grain size. Depending on the soil conditions, the load-bearing capacity is increased by means of a targeted primary or secondary grouting. Here, the Stump-system steel-tube piles prove particularly suitable as they can be designed in the form of steel-sleeve tubes.

2.2 Load-bearing Systems and Wall Connections

The foundation improvement must guarantee that the building loads are safely transferred to the subsoil via the pile foundation with various pile arrangements to be chosen from.
Normally, a centric individual pile arrangement below a wall can only be achieved through installation of piles in a wall recess. This means the wall has to be broken up and closed again with masonry or concrete after the pile has been installed. The

problem involved in this arrangement is that the piles must be safely protected against flexural loads resulting from non-intended eccentricities.
Two-pile systems in interlocking-sword or parallel arrangement are more favourable under structural aspects. In the case of an interlocking-sword execution, inclined piles are arranged in the masonry and/or foundation on both sides (Fig. 2). Provided the quality of the existing structures is sufficient, the piles are often directly connected to the foundation via bonding. When concrete grout is used in the area where the existing structures are penetrated, the bond length to DIN 1045 can be extremely reduced. Any expanding loads which might occur must be allowed for using anchor bars or masonry bows.

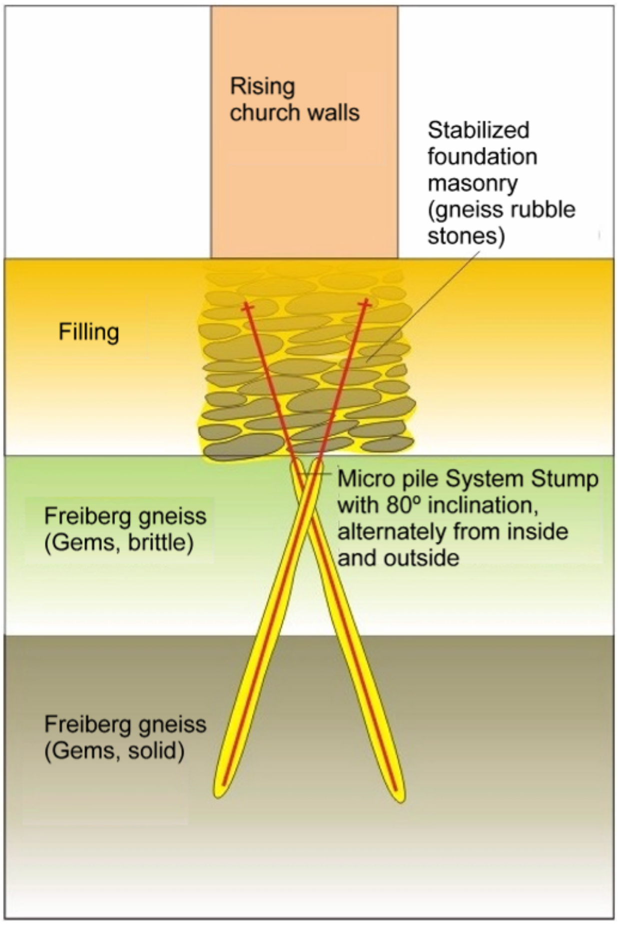

Fig. 2: Interlocking-sword pile arrangement at foundation penetration(Jacobi Church, Freiberg)

In those cases where bond length or existing masonry or concrete qualities are inadequate, installation of a wall plate is required. For the arrangement of wall plates the wall load is first transferred to a wall plate via insertion girders or supports, and then to the piles (Fig. 3). Both insertion girder and wall plate must be so designed that they allow for both flexural loads and lateral forces. Furthermore, they must be so dimensioned that the admissible masonry tensions in the existing building are adhered to. Likewise, the wall loads can also be transferred to the wall plate via shear bonding. This bonding can be increased by means of an interlocking connection and/or pre-stressing using horizontal tendons.
For foundation improvement purposes and the underpinning of individual columns, the wall plates are replaced by surrounding sleeves or collars.

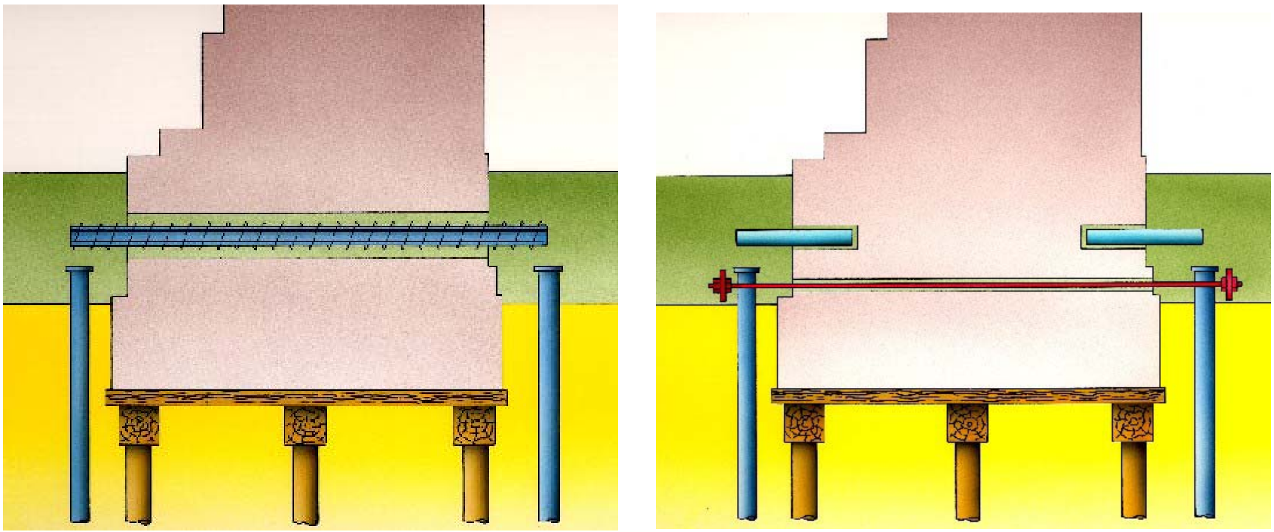

Fig. 3: Insertion girders and wall plates in parallel pile arrangement (New Museum, Berlin)

A special pile arrangement may be required owing to the fact that the wall is only accessible from one side. In this case, the so-called “rampant” or “one-sided” constructions are used where the wall load is transferred via a support to a pile located next to the wall. For absorption of the resultant moment inclusion of a tension pile might be required (Fig. 4).

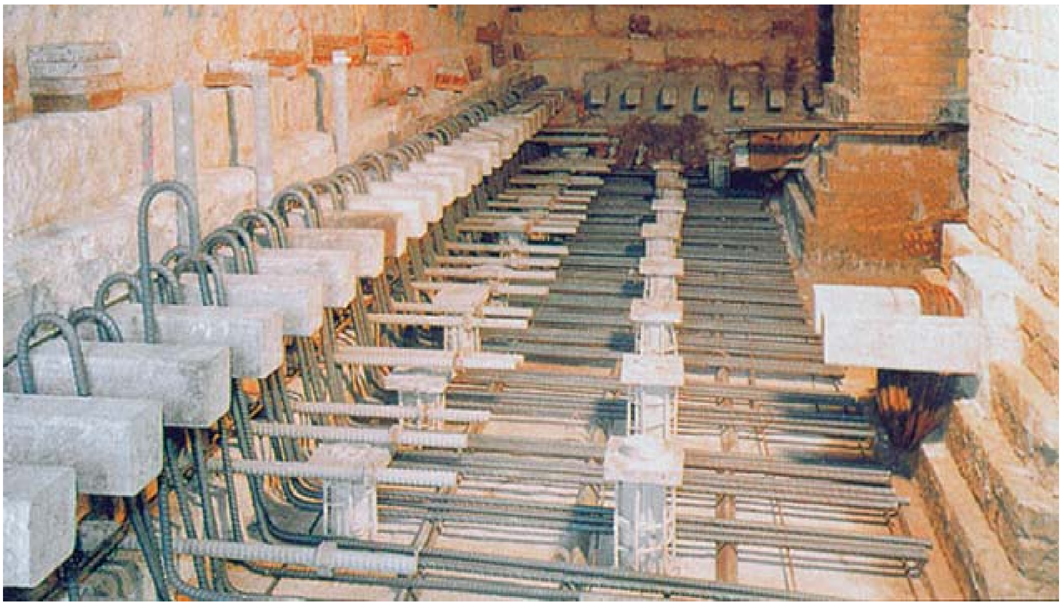

Fig. 4: “Rampant“ construction (New Museum, Berlin)

3. Case Histories

3.1 Museum Island, Berlin

3.1.1 New Museum Project, Museum Island in Berlin

In 1841, King Friedrich Wilhelm IV. of Prussia ordered „the entire Spree Island behind the (royal) museum to be converted into a meeting place of the arts and sciences“. This order marked the beginning of the singular history of the Museum Island in the centre of Berlin. The first building to be erected, between 1841 and 1855, was the New Museum, based on the design by the architect Friedrich August Stüler. The building was severely damaged during World War II, parts of it completely destroyed. Reconstruction did not start until 1990. To begin with, the foundation had to be rehabilitated using micro piles. The museum is scheduled to be re-designed by 2009, based on plans by the British architect David Chipperfield, and incorporating the existing structures.

3.1.2 Site Conditions and Excecution

The foundation soil met on the Museum Island is as follows: a ca. 15 m thick non-load-bearing, soft muddy layer is covered by an up to 5 m thick fill. The medium-dense to dense layers of ice-age sands met further down are optimally suited for the building load transfer from micro piles (Fig.5).

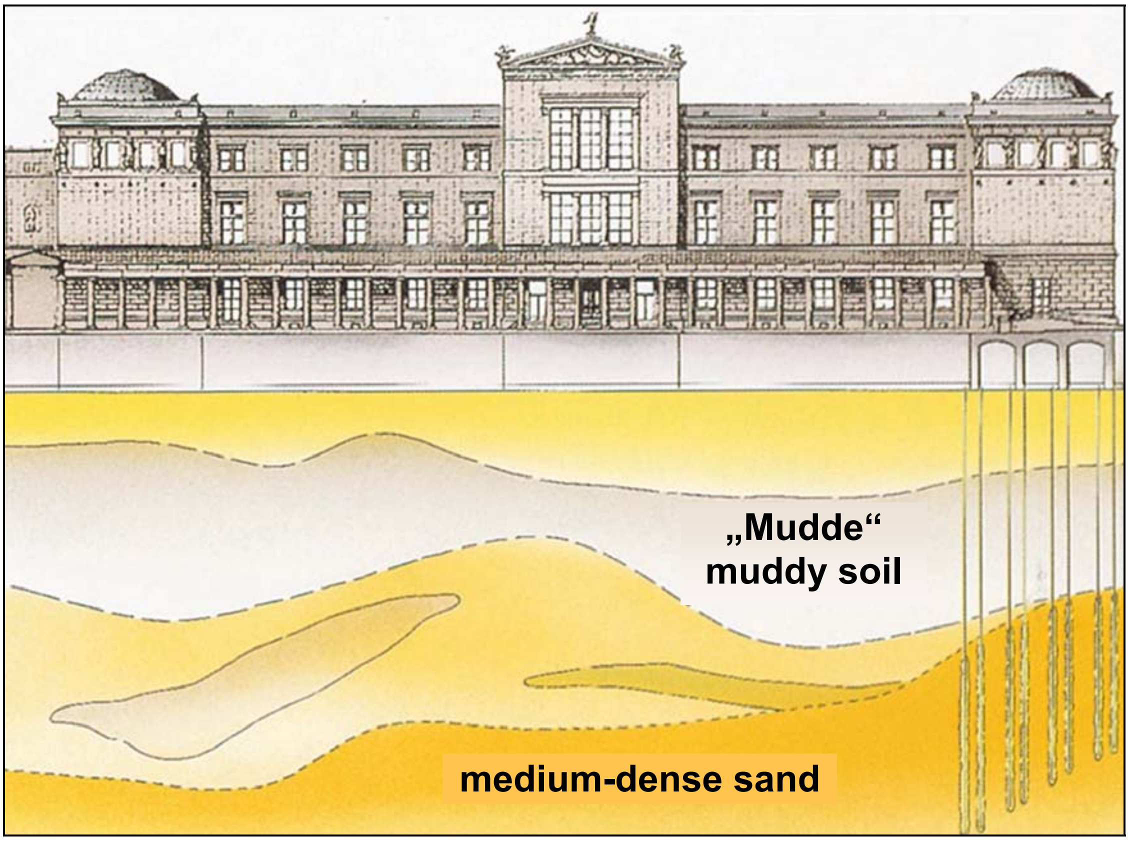

Fig. 5: Foundation soil situation at the New Museum in Berlin

Owing to the unfavourable foundation soil conditions the museum was founded on timber piles at that time. In the course of construction works carried out near-by the groundwater level was lowered and, as a result, the pile caps of the timber-pile foundation were exposed to constant changes from dampness to drying out, with the supply of oxygen. The resultant rotting had meanwhile reached a stage where the original cross-section was found to be damaged to 70 % on the average, in some areas to up to 95 %. It was determined that under these conditions the foundation needed comprehensive rehabilitation. The rehabilitation concept was based on

relocation of the vertical loads from the existing defective timber piles to new micro piles.
To protect the existing foundation situation against negative effects, one pile row each was arranged on both sides of the old beam ties (Fig. 3). Based on a special proposal submitted by Stump Spezialtiefbau GmbH, about 1600 Ø 80 mm Stump-system tube piles were employed. The unfavorable foundation soil conditions were accounted for by a wider pile shaft diameter of 240 mm. A secure bond between the foundation soil and a dense pile concrete was achieved by an intensive, phased grouting of the pile shaft. This is where the tube pile, designed in the form of a sleeve tube, proved particularly advantageous as it facilitated a targeted post-grouting.
The test loads applied on 5% of all piles confirmed the required 800 kN load transfer with double safety.
The drillings for the piles foreseen inside the building had to be carried out using special drilling gear, as the room height was only 2.30 m in most cases (Fig. 6). In some cases, the weathered timber piles had to be drilled through over their total length using special equipment as for lack of space a relocation of the piles proved impossible.

FIG. 6: Drilling operations for pile manufacture

To check the foundation soil situation and identify drilling obstacles, all relevant drilling data such as feeding and feed pressure were continuously recorded during drilling. In view of the fact that a carefully executed injection was equally decisive for the durability of the foundation work, each injection operation was recorded in every detail via a pressure-quantity recording device.
The drillings for insertion and/or through-girders in the existing foundations were carried out as core drillings with particular care. Installation of the girders was

followed by special mortar grouting to ensure an optimal frictional connection (Fig. 4).

3.2 St. Kolumba, Cologne

3.2.1 Project

In Cologne, the Church of St. Kolumba was destroyed by bombs during World War II. A museum has now been built on the historic grounds, at 12 m above ground level. Realization of this ambitious building was only possible by the use of micro piles bored into the sandy ground all the way through the over 600-year old walls of the destroyed church.

Fig. 7: Site situation before WW II and 2001 with 'Böhm'sche' Chapel

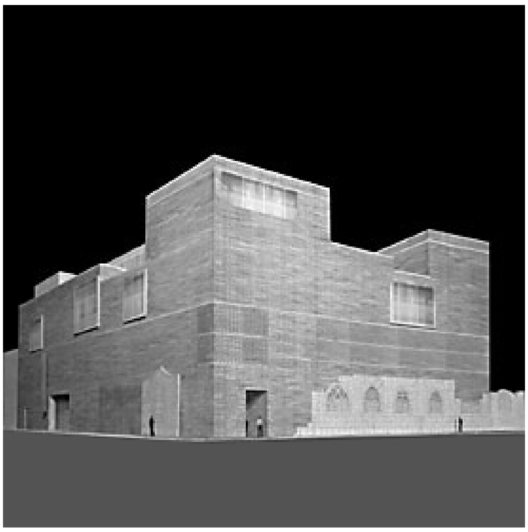

Fig. 8: Architect's design by Peter Zumthor, construction of new museum on the ruins

According to the design by the architect Peter Zumthor new, light-transmitting leaves consisting of so-called "knitwear" masonry ("Pullovermauerwerk") (bricked up in an

open-work pattern) are foreseen to be constructed on the remains of the external masonry, ending in an initial floor at a height of 12 m above the intra-mural digging field. The two-storeys of the Diocesan Museum exhibition rooms are constructed on top. The digging field remains an open archaeological zone and will be accessible via foot-bridges. Slender, filigreed heavily loaded steel columns in both external walls and the intra-mural section support the loads of the newly built structure. The existing 'Böhm'sche' Chapel is integrated into the hall so constructed. The columns are to be harmoniously fit into the external walls of the ruins without exerting any additional loads on the masonry or unnecessarily interfering with the existing structure. These columns in the external masonry are later referred to as "implants". Fig. 9 gives a cross-section through the digging field up to the first floor. The slender internal columns and implants in the external masonry are clearly visible. The light-transmitting "knitwear masonry" is erected on top of the external masonry.
Implementation of this architectural design in the form of a structural design was carried out by the Dipl.-Ing. ETH/SIA J. Buchli (Haldenstein, CH) und Dr.-Ing. Schwab und Lemke (Cologne, FRG) group of consulting engineers.

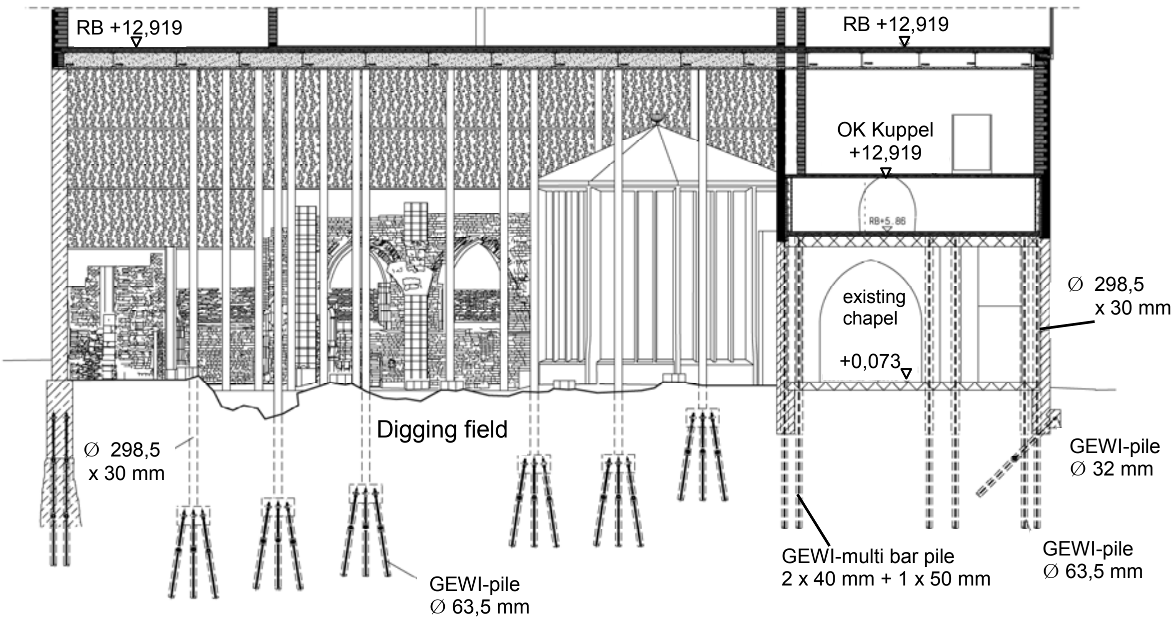

Fig. 9: Cross section

3.2.2 Site Conditions and Execution

To ensure appropriate realization of the architectural design, comprehensive preliminary investigations were required. First of all, two test drillings through masonry pillars were carried out in 1999/2000 and these showed that the very heterogeneous material can be drilled through with adequate accuracy.
As a next step, two test piles, designed as multiple-bar piles for the intended working load of 200 kN, were manufactured in 2001. The load application section of the piles was located in the non-cohesive soil layers of the Cologne Rhine terrace. One by one and in phases, the test piles were exposed to a load of up to 4000 kN, i.e. 2 times the planned working load. The loads were applied with interim load removals after each loading phase. Fig. 10 shows the load displacement on test pile G1 with a 14-metre grout box length.

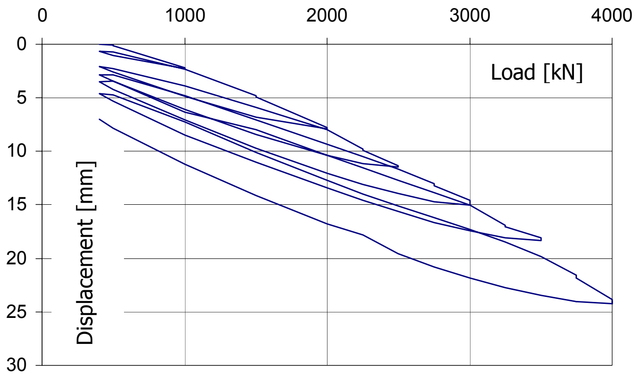

Fig. 10: Load displacement diagram for test pile G1 (l_v=14 m)

Work for construction of the new museum began in 2003. Again, Stump Spezialtiefbau GmbH was awarded the specialist underground works in its capacity as sub-contractors of the company Heitkamp / Cologne branch.
According to the execution planning, pile-foundation implants were foreseen at 30 locations in the area of both external wall and chapel. An implant comprises a thick-walled, Ø 298,5 x 30 mm steel tube which transfers the eccentric structural loads from the new structure to the foundation. This steel tube absorbs occurring moments and horizontal loads and transfers same through the historic external wall area. For corrosion protection purposes, a Ø 330 x 5 mm high-quality steel tube is positioned around it. Both tubes were delivered to site after having been factory-connected over their full length. Depending on both height of the external wall remains and lower edge of the existing foundation, the length of the implants varies between 9 and 12 m. Load transfer takes place via the thick-walled steel tube, without connection to the external masonry. In the area of the foundations, stay tube and high-quality steel tube are perforated over a length of 4 m so as to allow a horizontal load transfer in this area. Load transfer is achieved by filling the space between thick-walled steel tube and high-quality steel tube. Through embedding of the foundations in the foundation soil and owing to the externally orientated pier aprons all horizontal loads occurring can be transferred, and in areas where embedding is uncertain, special support constructions are foreseen. For this purpose, two GEWI piles with an inclination of 60° are drilled into the digging field area from the outside and some 2 m below the ground surface. The GEWI Ø 32 mm composite piles with double corrosion protection are interconnected at the top by means of a short concrete cushion (l=1.2 m). This concrete cushion is interlocked with the existing masonry in a stone-cutting pattern and the masonry was stabilized in this area through application of a borehole suspension.
Load application in the pile cap area is guaranteed above the masonry debris by means of a surrounding reinforced pile cap beam. This beam incorporates a cap and equalizing construction which transfers the load from the rising steel tubes in the “knitwear masonry“ (“Pullovermauerwerk“) to the implants. Slightly below this beam tie the load is transferred to the Stump-system composite piles. For this purpose, the implant tube is completely filled with cement. Load application from the implant tube to the piles is carried out via approved anchor elements fitted to the composite pile cap.

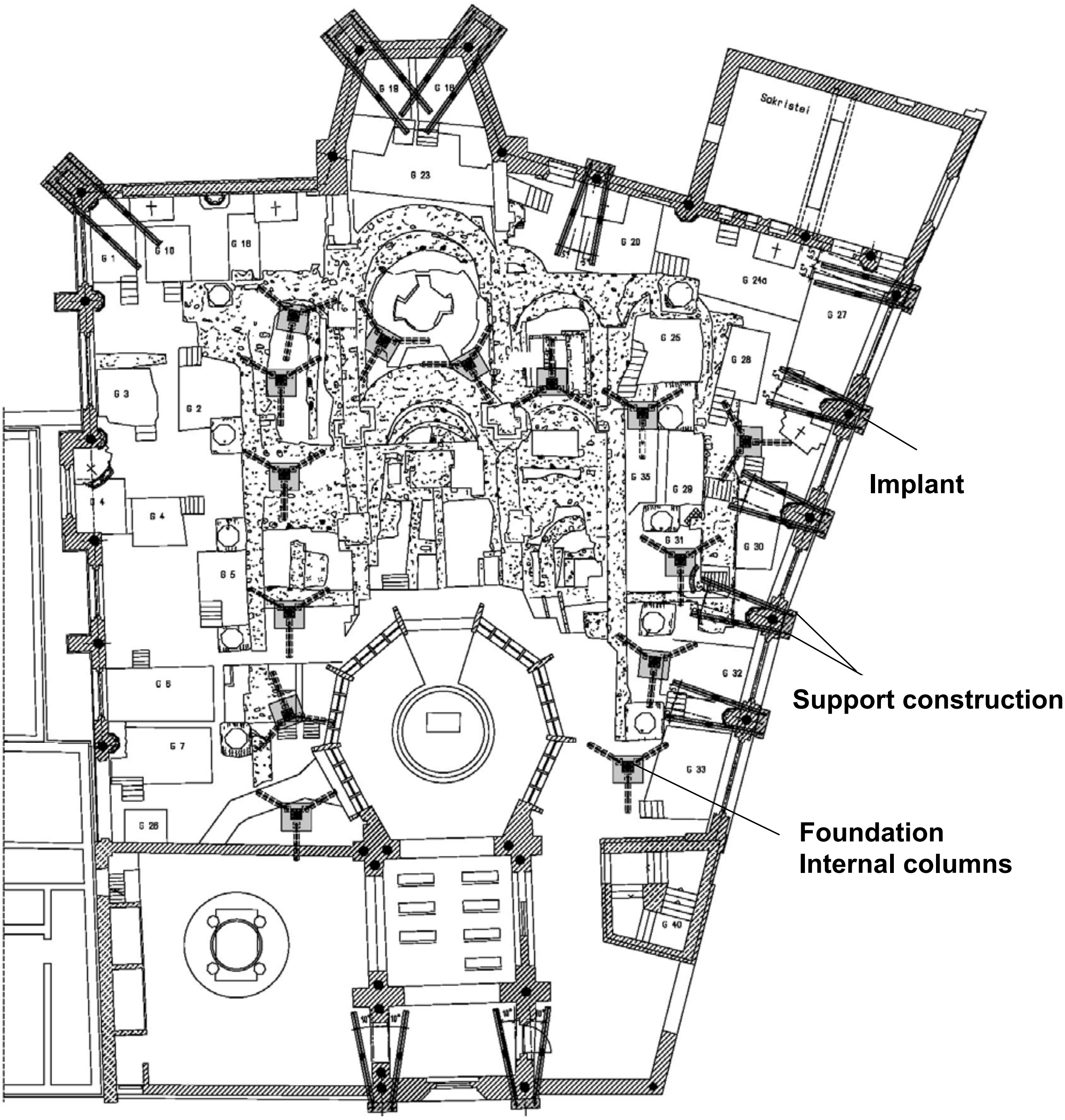

Fig. 11: Plan view with foundations in digging field and external wall implants

The implant tube is used to carry the composite piles all the way down into the load-bearing strata of the Rhine terrace. Depending on the height of the existing external walls and the forces at the load point the piles chosen are up to 30 m long. Complete vertical load transfer takes place via the composite piles. The working loads of the implants in the external wall area range between 250 and 1350 kN. Therefore, composite piles with double corrosion protection and designed as single-bar piles with a Ø 63.5 mm GEWI load-bearing member are used for piles under 1000 kN, or, for pile loads above 1000 kN, multiple-bar piles consisting of GEWI 2 x Ø 40 and 1 x Ø 50 mm. Fig. 12 gives a cross-section of the implant.

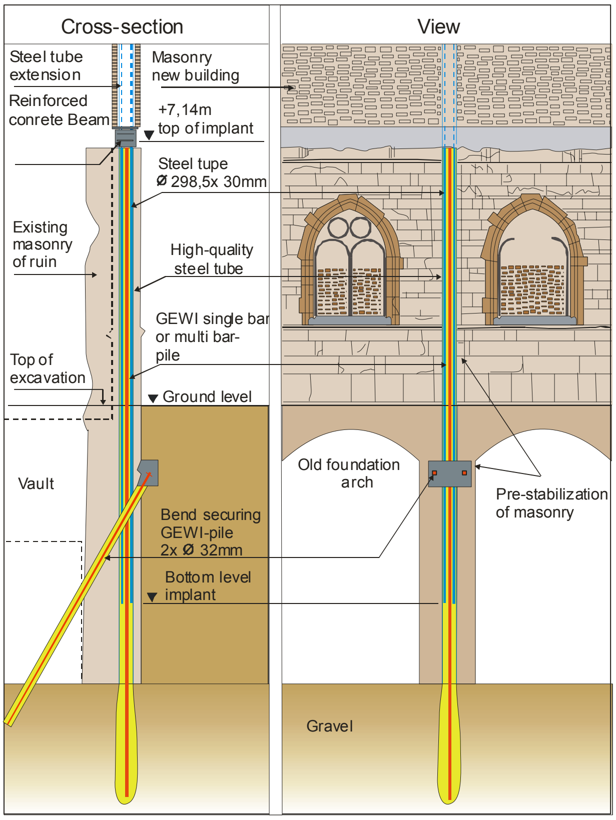

Fig. 12: Cross-section of an implant

Manufacture of the implants was carried out as follows. To begin with, the wall around the drilling area was provided with a timber support construction, and then drilling platforms were set up reaching beyond the top of the wall. For technical reasons, complete walls were simultaneously provided with scaffoldings, with 6 to 7 drilling points in each case.
The working platforms to a height of up to 9 m were designed for a drilling gear weight of 20 tons plus 10-ton advance and backhaul forces. With the scaffolding so dimensioned it was possible to have the drillings carried out using 'Klemm 806/3' heavy-duty anchor drilling gear. The working platforms were provided with a fully accessible working level. In the area of the northern wall which aligns with the double-storey deep basement building-pit, the platform had to be erected cantilevering over part of the building pit.
After the drilling platforms had been set up the drilling points for the core drillings were identified and prepared on the wall crest, and this was followed by a Ø 100 mm preparatory drilling to bottom level of foundation in core-drilling method as dry-core drilling with puff blowing. This bore was filled with an AIDA-type borehole suspension based on the multiple-phase tremie method. Following hardening of the fill material the core drilling could be sunk to a diameter of 350 mm. During drilling operations the deviation was monitored based on target data plates and plumb bobs; after completion of the core drilling the entire drilling section was surveyed using inclinometers, and the deviations noted were below 0.5%.
All in all, the core drillings were sunk by means of up to three drilling installations. The mean drilling speed for the Ø 350 mm core drillings was 3 - 4 m per working day. After the drillings had been surveyed and the admissible deviations checked, all implants of a wall could be installed using a site crane. The implant tubes were securely aligned both in respect to levels and position. After installation of the

implants the pile drillings could be sunk using an anchor drill gear to Ø 219 mm and based on the twin-point drilling method. In view of the pile lengths involved part of the piles had to be joined on site.
Following pile installation the piles were grouted with cement suspension. The first cement fill reached up to ground level. After the cement had hardened the cement fill was completed up to approx. 10 cm below top of implant. The upper section of the pile up to top of implant was filled with 'Pagel' sealing mortar V1/50. Fig. 13 shows the drilling operations carried out on the foundation piles of the 'Böhm'sche' Chapel.

Fig. 13: Drilling work from working platform

In the interior, the execution planning provided that the main ceiling construction be supported on steel columns at 14 locations. The former interior of the church with its digging field is heavily fissured in elevation and consists of a large number of monuments worthy of preservation such as pier remains, vaults and altar sections. Location and number of internal columns were determined in close co-operation between structural engineers, architects, and the representatives of the Department for Ancient Monuments in minimal number and dimension and guided by the common objective of preserving the existing structural remains. The steel tube columns (Ø 298,5 x 30 mm) supporting the ceiling construction are up to 16.70 m long. These columns end in an individual foundation embedded in the digging field. Further load transfer takes place via a pile block consisting of 3 No. Ø 63.5 mm GEWI composite piles with double corrosion protection and individual lengths ranging between 9.0 and 12.5 m. Fig. 14 gives a cross-section of an internal-column foundation.
For pile manufacturing, the entire construction area in the church interior was covered with heavy-duty scaffoldings designed to allow for the drilling gear weight.

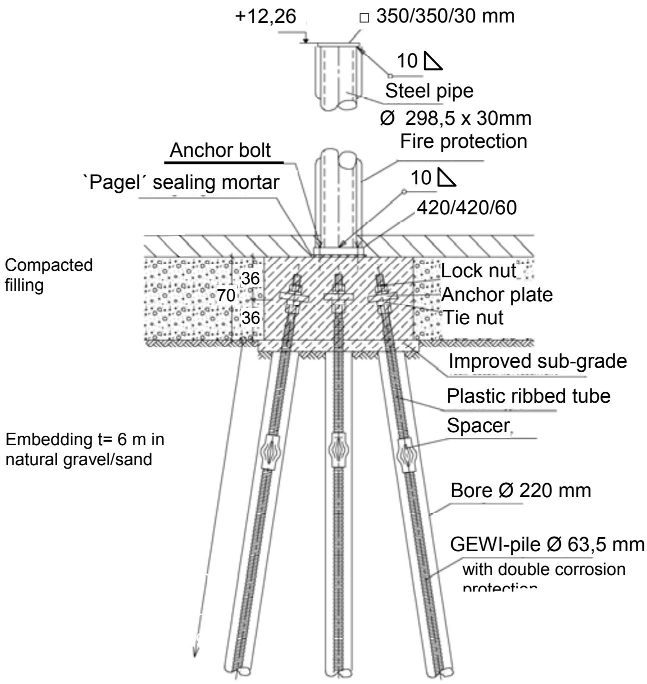

Fig. 14: Pile-founded internal-column foundation

Part of the drilling starting points were up to 6 m below the heavy-duty scaffold. Owing to the small number of load application points scaffold support proved difficult so that major distances had to be bridged in some cases. Fig. 15 shows parts of the still uncovered digging field. Small service and working routes designed for the drilling gear loads consisting of dead weight and working operations were provided for the drilling gear above the pile starting points. In addition, this scaffold was only dimensioned for loads resulting from the stored material.

Fig. 15: Digging field surface

To ensure true-to-level pile manufacture, a drilling pattern was prepared to guide the casings in respect to location, inclination and direction. For some foundations where more space was available the drilling pattern was pre-fabricated in steel and used several times. The pattern was fit in and securely positioned in place. For some individual foundations characterized by minimal dimensions owing to their position

inside the vaults special timber patterns were prepared which could, however, only be used one single time.
With these drilling patterns all 42 composite piles of the interior section could be manufactured true to level.
Fig. 16 shows the manufacture of the foundation piles in the covered-up digging field. The photograph was taken from a high-rise crane. The 'Böhm'sche' Chapel is clearly visible as is the drilling gear set with storage space for the pile material. At the areas above the pile starting points the pile manufacture working level could be opened.

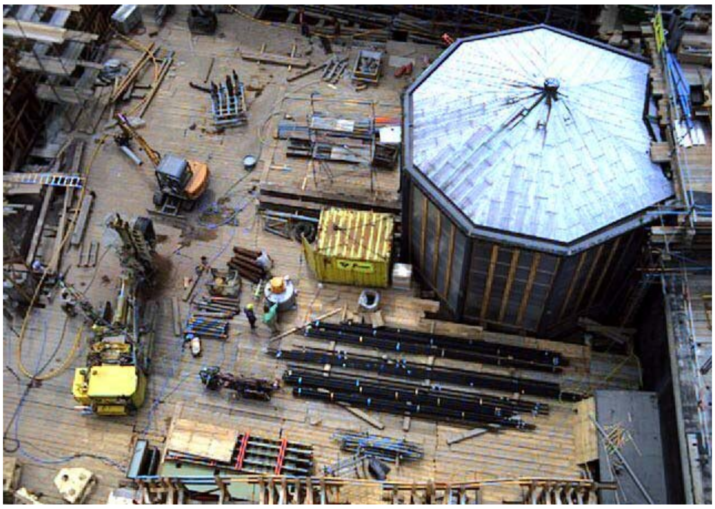

Fig. 16: Drilling work in the area of the digging field

4. Summary

State-of-the-art foundation improvements and underpinnings are required for the conservation of historic monuments which are in need of rehabilitation owing to their structural decay over the years, or whose structural stability is at risk owing to new construction measures, and that of structures altered as a result of reconstruction measures with major load increases. Some of the construction projects carried out successfully have been chosen here as an example to show that micro piles offer a technical and cost-efficient stabilization system which can be used in all soil types and for numerous foundation systems. The advantages provided by foundation improvement based on micro piles are the system's favourable deformation properties. Such minor deformations can even be minimized further by preloading, if need be.
Under the aspect of the conservation of monuments the use of micro piles is to be judged favourably as building substance and outer appearance of a historic foundation remain largely unharmed even though it has been deprived of its function [5].

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