

Foundation analysis and restoration of a 13th century church founded on lacustrine clay

Analyse de la fondation et rétablissement de la structure d'une église du 13ème siècle fondée sur des argiles lacustres

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ABSTRACT: Soft Lacustrine Clay forms the subsoil near most of the Pre-Alpine lakes. These areas have been densely populated for many centuries. Many of the historical buildings remain and these have inadequate foundations and difficult construction conditions. This paper deals with the investigations for the necessary restoration of the foundation and the structure of the Trinity Church at Constance, Germany. After the implementation of immediate stabilization due to the extremely low safety conditions, subsequent steps are planned using the observational method. Finally, the measurement program and the construction sequence are described in detail. Some results of settlement and tilt measurements are presented. Key words: Lacustrine Clay, Foundation, restoration, observational method, inclination, settlement, measurement

RÉSUMÉ: Les argiles lacustres constituent le sous-sol autour de la plupart des lacs pré-alpins. Ces régions ont été très peuplées pendant des centaines d'années. Il existe beaucoup de sites historiques et ceux-ci ont des fondations insuffisantes et des conditions de construction difficiles. Cette publication décrit les analyses faites pour le rétablissement de la fondation et de la structure de l'église St. Trinité à Constance, Allemagne. Après une stabilisation immédiate, nécessaire à cause de la mauvaise sécurité du bâtiment, des mesures ultérieures avec la méthode d'observation sont envisagées. Finalement, le programme des mesures et la séquence de construction sont présentés en détail, ainsi que des résultats de tassement et d'inclinaison. Mots clefs: argiles lacustres, fondation, rétablissement, méthode d'observation, inclination, tassement, mesures.

1 INTRODUCTION

In European Pre-Alpine regions, lakes and former lakes are found to have been formed by post-glacial events which left large areas of weak Lacustrine clays (Amann & Heil 1995, Springman et al. 1999). These areas have been populated for many centuries due to the favorable living conditions there. In the Middle Ages, a number of buildings which are now considered to be historical, were built on foundations of poor quality. Originally, these buildings were founded on horizontal or vertical wooden beams which have since rotted, for example, due to the lowering of the groundwater table (Wenzel 1981).

The Trinity Church was a part of the Augustine cloister founded in 1268 (fig. 1). The structure attained historical significance as the assembly church for the Constance Council in 1414. Afterwards the nave was furnished with precious frescoes which were completely uncovered in 1906. In 1877, a renovation of the eastern side was carried out involving the addition of the two symmetrical stair towers.

The level of the street in Constance and the top of floor level in the church were also raised in 1877 by approximately 1.35m due to the construction of a railway and because of reoccurring flooding of the Lake Constance.

It was first observed in 1901 that the approximately 1m thick longitudinal walls of the nave had experienced a "protrusion" of up to 0.45m towards the north. Even to this day, the cause of this inclination could not be determined with certainty. The inclination brought about, among other things, cracks in the outer walls, in the church roof as well as between the nave and choir (AICON 1998/1999).

2 CONSTRUCTION GROUND

The Trinity Church is situated in the old city of Constance in the area of moraine from the Würmian Ice Age. In addition to the moraine, Holocene deposits from Lake Constance on the soft Lacustrine Clay from the Pleistocene Ice Age are to be expected. Underneath lies a gravelly boulder clay of variable extent. The

local construction ground conditions were investigated during the preliminary planning of the restoration by a total of 3 borings with core samples and 12 CPTs (cone penetration test) down to 50 m respectively 30 m (fig 2). The boreholes were equipped with SOLEXPERTS trivec measuring devices, which measure vertical and horizontal deformations (x, y, z) of the ground (Thut 1997) In addition, a system of GLOETZL pneumatic pore water pressure cells was installed.



Figure 1. Interior of the Trinity Church at Constance, May 1999

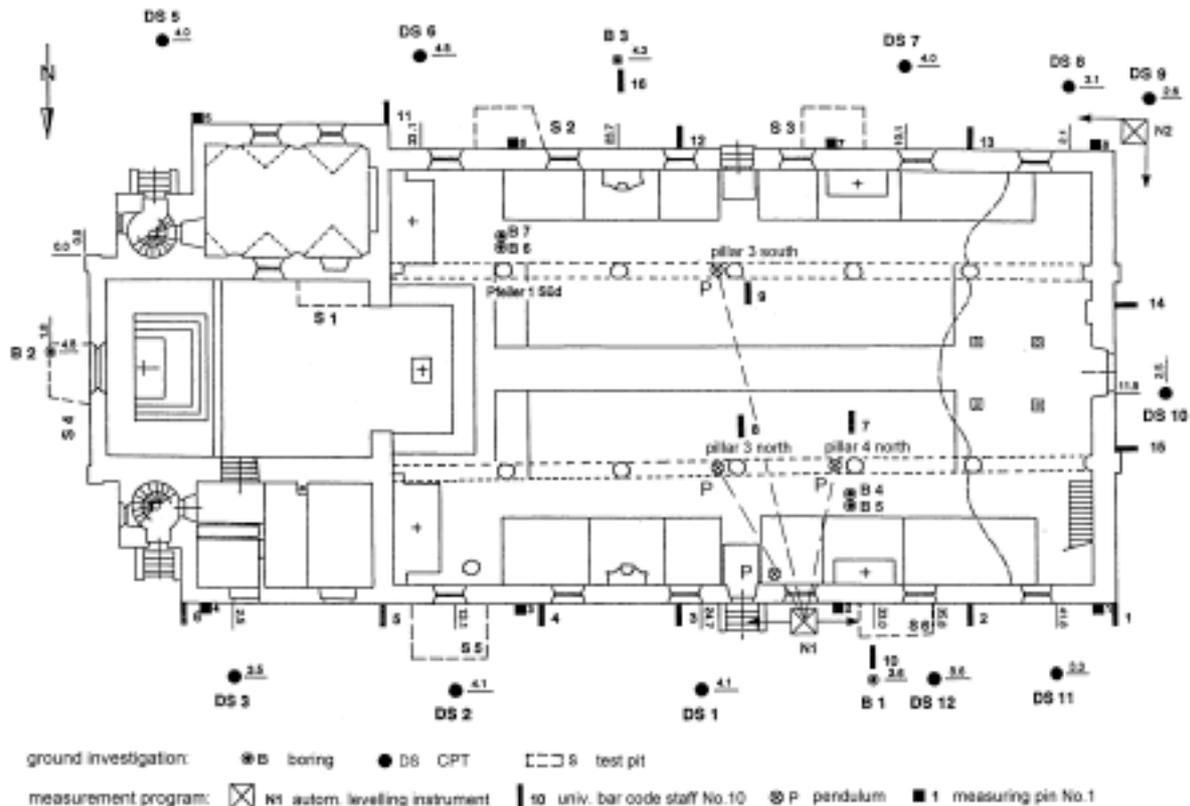


Figure 2. Ground plan Trinity Church, construction ground investigation and measurement program

The foundation of the outer walls was investigated with six test pits down to the foundation base. At four pillars inside the church, 4m deep borings were carried out through the floor surface down to the natural soil. According to the investigations, the foundation level of the outer walls lies an average of 2.2m under the natural ground level and the foundation level of the pillars is 3.3m under the current church floor. The highest groundwater level is expected to reach the depth of the foundation level of the outer walls. This corresponds directly to the water level of Lake Constance in the top soil layers.

The on site investigations agree with the geological expectations down to the level of the expected lateral moraine. The soil profiles near the surface of the northern and southern sides of the structure are, nevertheless, different (fig. 3). Especially two points are of main interest: On the northern side the Lacustrine Clay is approximately 16m but on the southern side it is only about 11m thick. While the natural layers are present below the foundation level on the northern side, these have been covered over by about 1m of construction waste fill on the southern side.

Table 1 presents the average soil parameters of Lacustrine Clay determined on the basis of field and laboratory tests (IGT 1991). From a soil mechanics point of view, Lacustrine Clay is a normally consolidated clay of low plasticity. The clay fraction consists of chlorite, illite, kaolinite and smectite minerals plus mixed layer minerals. The CPTs show that the Lacustrine Clay is pasty to soft, highly varved (varved clay) and very sensitive (fig. 4) (Amann & Wollenhaupt 1983, Heil et al. 1997). Fine sand layers are present in the clay which assist in consolidation following changes in pore water pressure. The cone penetration tests furnished a point pressure value of $\sigma_s=0.3$ to 1.7MPa. The deduced initial strength is $c_u=10$ to 50kPa with an average value of 20kPa (Edelmann 2000).

Corresponding to the glacial formation, the transition to boulder clay is smooth. The stiffness of the boulder clay increases rapidly with depth. In the silt of the boulder clay, SPT (standard penetration test) values of $N_{30}=10$ to 39 blows were measured, corresponding primarily to a semisolid consistence. In the sand

and gravel 52 to 94 blows were recorded corresponding to very dense bedding.

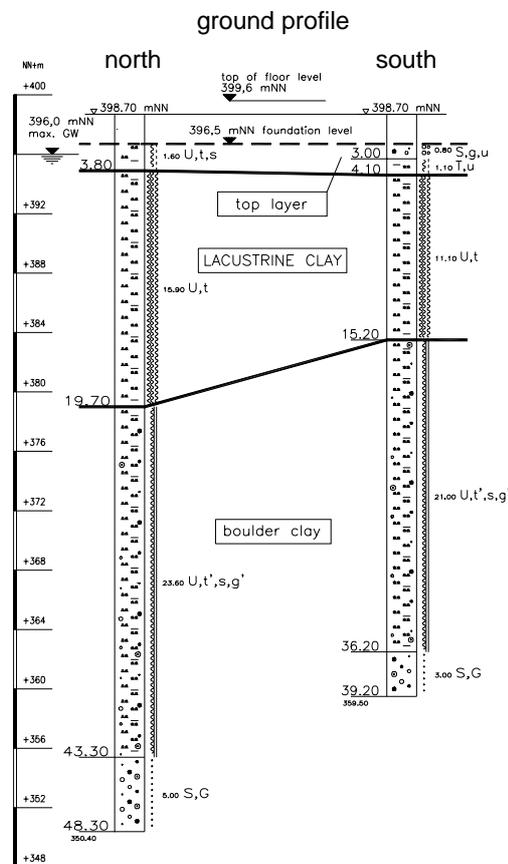


Figure 3. Typical ground profile

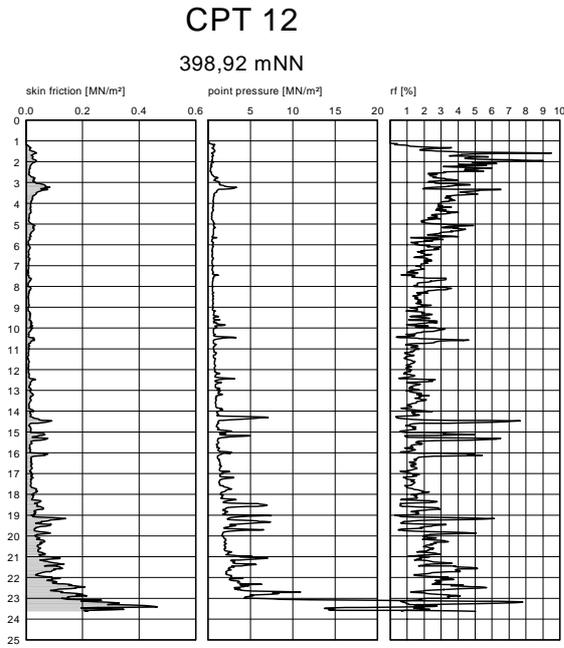


Figure 4. Typical cone penetration test profile

Table 1. Geotechnical parameters of Lacustrine Clay

grading values	friction angle	cohesion	undrain. cohesion	liquid limit	consist. index	compr. modulus
C,S,S,G	ϕ'	c'	c_u	w_L	I_c	E_s
[%]	[°]	[kPa]	[kPa]	[%]	[/]	[Mpa]
42/50/7/1	15 ÷ 20	0 ÷ 5	20	33.2	0.25	2

3 STRUCTURE

The Trinity Church is a towerless masonry construction with one nave, two aisles and a framed wooden roof (fig. 5). The entire weight of the structure is approximately 8000 tons. The greatest loads exist in the stair area of the outer eastern wall. The original foundations are made up of large stone and block masonry walls with limestone mortar which were built on planks or plank grill-works. The reconstruction of the choir at the end of the 19th century was constructed on lean-mix concrete foundations.

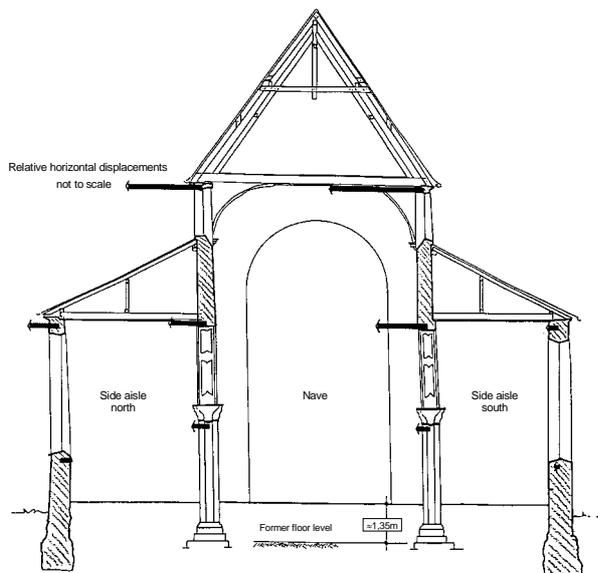


Figure 5. Geotechnical restoration concept

The width of the foundations under the 0.8 to 1.0m walls varies between 1.0 and 1.5m. The pillar foundations were formed as rough squares with a surface area of approximately 1.8 x 1.5m with a corresponding average soil pressure of $\sigma=550\text{kPa}$. The calculated soil pressure under the strip footings of the walls averages 220 and 500kPa. The resulting safety with respect to static ground failure is $\eta=\sigma_f/\sigma_o=1.0$ to 1.4, predominantly $\eta\approx 1.0$ (calculated according to German regulations DIN 4017 with $\eta_{\text{eff}} \geq 2.0$), depending on the width of the investigated foundation.

The maximum measured out of plumb deviation in 1990 of the 16 m high nave walls with wall pillars of 0.9m diameter was 0.56m. During the preliminary investigations carried out between 12/95 and 06/99, settlements between 2.2mm (south) and 3.3mm (north) were measured. The average settlement rates measured with the trivec measuring device were between 0.6 and 0.9mm/year, with a maximum value of 1.2mm/year. The settlement difference increased on the northern side on the average of approximately 0.3mm per year (AICON 1998/1999). The back calculation for the period 1901 to 1990 resulted in an increase in the settlement speed factor of about 2. Also, the stability of the above-ground structure led to an extremely unfavorable evaluation of the situation, such that in 1995 it was decided to undertake stabilizing procedures for the structure and foundations immediately.

4 RESTORATION STEPS

4.1 Immediate actions

The original idea was to direct the horizontal buttress forces resulting from the inclination of the pillars in the gable and choir walls located at the end of the nave. The horizontal forces in these walls cause additional foundation loading due to bending moments in the direction of the inclination. The solution was to install horizontally placed trussed beams in steel at the height of the side aisle roof pillars on the northern (fig. 6) and southern side.

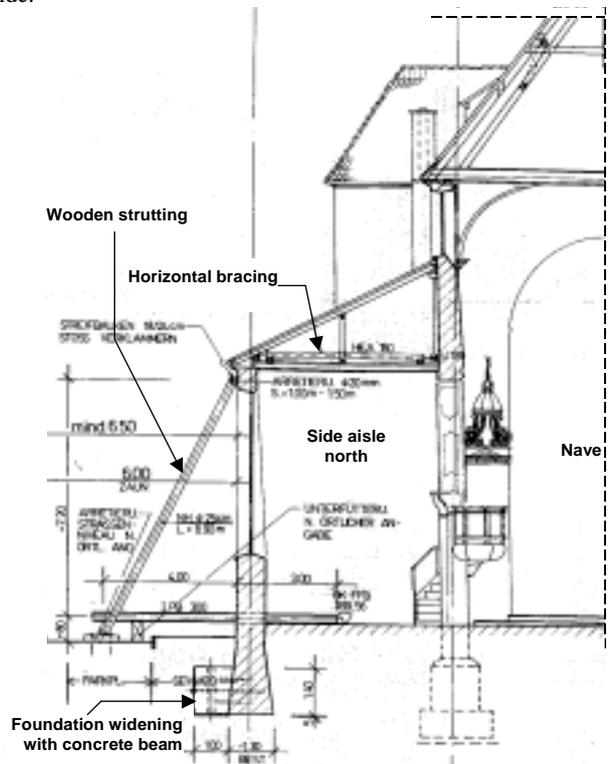


Figure 6. Different renovation work at the northern wall

Both bracings will be attached only to the neighboring gable and choir wall. No additional loads should be directed into the side walls because of their existing inclination. Forces, caused by the potential further inclination of the pillars, will be directed through the horizontal bracings to 50% each into the western gable wall and into the choir wall and through the corresponding foundations into the ground.

Within the framework of the geotechnical restoration concept presented here, the existing foundations in the area of the gable and choir walls will be strengthened and the existing original foundations will be widened using concrete beams in a first res-

toration stage. This is necessary in order to enable the additional loads from the horizontal bracing to be taken up. The concrete beams will be installed on both sides, bound together with the original foundation and prestressed against masonry walls using tie anchors. Previously, the grouting of the foundation wall will be carried out in order to fill weak spots such as empty cavities and cracks with grout and to guarantee a sufficient bond with the existing foundation. The approximately 1.4m high cast-in-place concrete beams will be placed in sections of about 2.5m length. The geotechnical restoration concept of the foundation is shown in fig 7 (AICON 1998/1999).

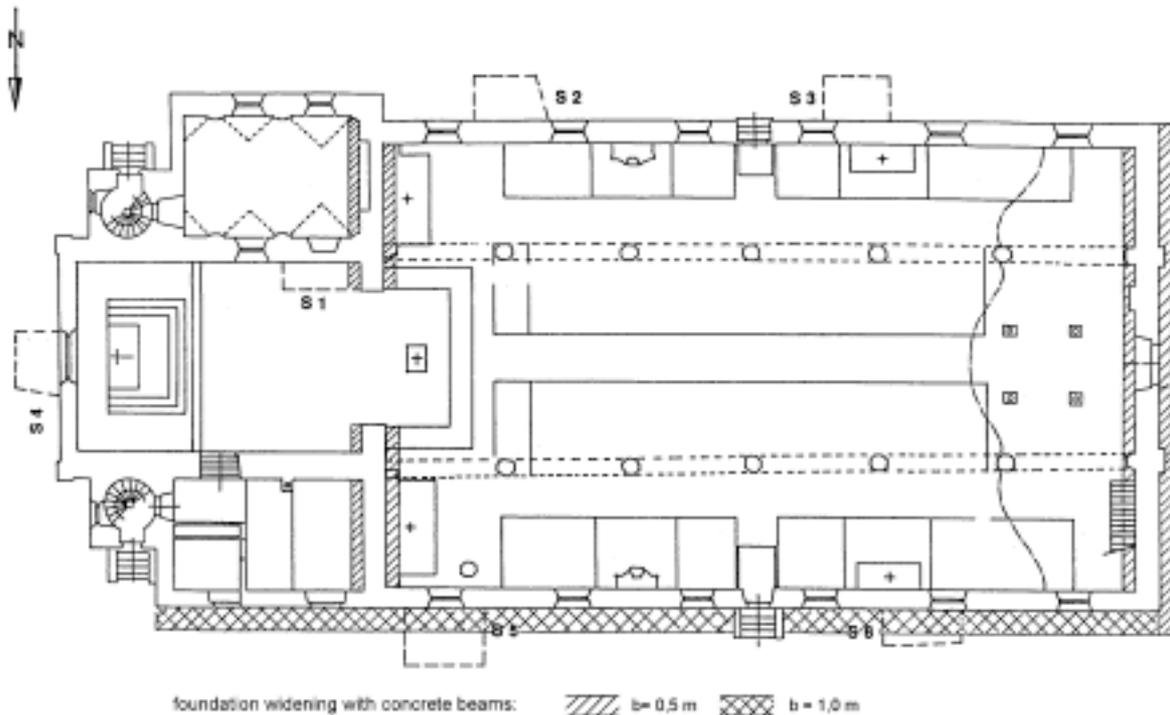


Figure 7. Geotechnical restoration concept

The already low safety level of the foundations requires additional safety constructions measures for the stabilization during the construction phase. Therefore, the northern wall will be supported with wooden strutting (fig. 6). Because of the sensitive construction ground and the low structural safety, each intervention would cause unavoidable deformations. These deformations are to be limited through a well-defined work schedule and observed by automated monitoring.

4.2 Subsequent actions

At the present time it can not be evaluated if the actions described in chapter 4.1 are sufficient to obtain long-term safety. Subsequent actions have to be considered in advance. Different possibilities of restoration of the foundations are shown in fig. 8.

Nevertheless, a step-wise procedure based on the observational method seemed to be the most effective approach. According to the extent of deformations observed the following steps involve a completion of the foundation widening and in addition the installation of cross beams. This is tantamount to a new raft foundation (fig. 8 c). Ultimately it could be necessary to place the structure on a pile framing (fig. 8 d) which is also equivalent to a new foundation of the Trinity Church. In this case, the eventual pile head coupling must be planned in advance of the foundation widening. The piles must be prestressed against the beam grillwork in order to guarantee the contact between structure and piles and to anticipate settlements due to the load changes. The most comprehensive solution will be to separate piles and con-

struction by adjusting devices for levelling after differential settlements (fig. 8 d).

The lack of space, as well as the extreme sensitivity of the structure and ground, limit the choice of pile types. In principle, only small diameter piles which may be grouted may be considered (Gudehus et al. 1987, Amann et al. 1988, Amann 1992, Giudici et al. 1996/1997). Field tests are necessary to clarify the possible pile installation and bearing capacity. Accordingly, a measurement program was drafted which is described detailed in chapter 5. The extent and the individual stages of the restoration depend on the results of the geotechnical measurements.

5 MONITORING

As a part of the ongoing monitoring, settlement and tilt measurements of the outer facades and of the pillars are carried out (fig. 2). For the monitoring settlement, 11 measuring points on the outer walls and 3 measuring points on the pillars inside the church were selected. At these points universal bar code staffs were installed. The universal bar codes were automatically read according to the given measurement cycle from one of the two automatic levelling instruments, day and night (Amann & Edelmann 2000).

The settlement of the southern wall of the side aisle and the gable wall to the West was measured with the levelling instrument positioned on the outer wall of the south-western corner of the building (fig. 2). The second automatic levelling instrument was mounted on the northern wall. This device also measures the settlement of the three pillars in the interior of the church through a small window. The reference points for the settlement

measurements which were also equipped with universal bar code staffs are located on two neighboring residential houses. It is assumed that the height of the references points do not change during the limited time period over which construction will take place. The measurement uncertainty of the precision levelling instruments is limited to 0.5mm.

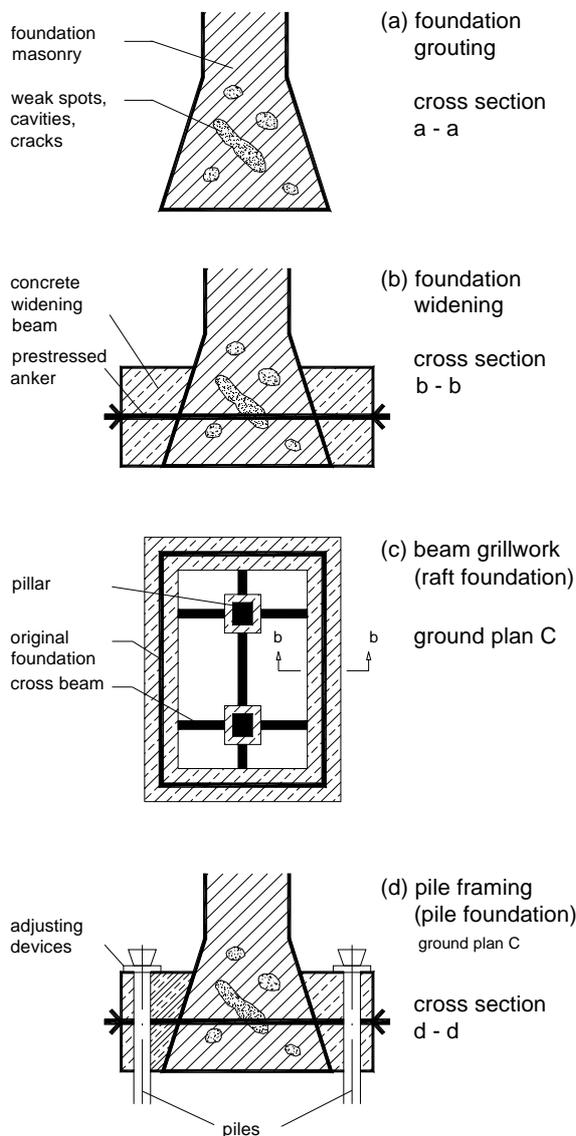


Figure 8. (a) – (d): Different foundation renovation steps

The inclination of the pillars was originally planned to be measured with stationary inclinometers. Out of consideration for the precious frescoes on the nave walls it was decided to carry out inclination measurements with pendulums. These were installed with a simple cantilever arm on the nave wall above the pillars (fig. 9). Three fixed displacement transducers were located on the approximately 12m long pendulum bars which permitted measurements of the horizontal displacements. The inclination will be calculated using these values. The horizontal displacement transducers work very precise with a limit of uncertainty of 0.1mm.

A total of 4 pendulums were installed, with 3 on pillars and one on the interior of the northern wall. The pendulum on the northern wall is 8m long and is located in the central wall section where the largest inclination of approximately 0.36m occurred (fig. 2).

The installed instruments are permanently and continuously monitored, stored and controlled by GeoMonitor software, specially designed for monitoring up to hundreds of sensors. All sensors are connected with one bus line to the measurement control centre using an appropriate controller system. The visualisation of the measurements is enabled with SOLEXPERS DAVIS software. The Data Visualisation software is installed at selected external stations, at the AICON office and at Solexperts and is used for graphic representation.

The automatic measuring station with GeoMonitor permit the consideration of threshold values and activates an alarm if these values are exceeded. For this case an emergency program is available to protect persons and the structure with appropriate supporting measures. Such automatic warning measurements have been improved at different construction sites especially in Berlin several years ago (Thut 1997).

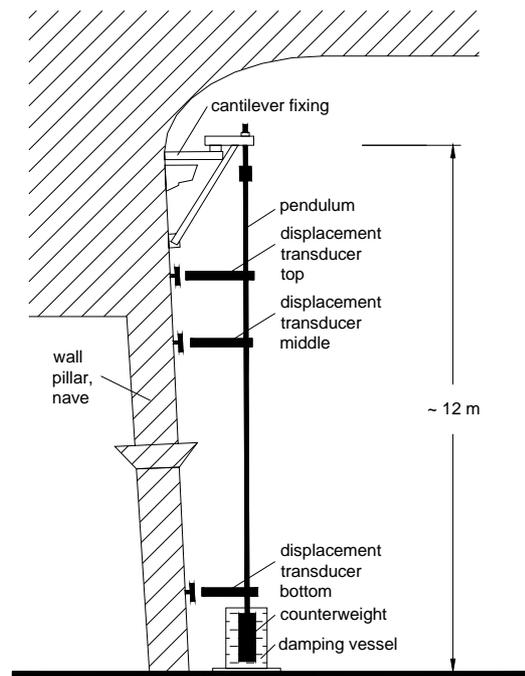


Figure 9. Different renovation work at the northern wall

6 CONSTRUCTION SEQUENCES AND RESULTS

The measurement program was installed in May 1999. The monitoring instruments showed a stable trend for the measurement values. After finishing preliminary work in July 1999 the restoration work could not be started because of the unexpected high water level of Lake Constance due to snow melt. At that time the groundwater level in the old city of Constance was approximately 1.2m above the foundation level of the Trinity Church and was observed by groundwater measuring gauges.

Restoration work started in October 1999. First, the timber work for the propping of the northern wall with struts was carried out. The process of prestressing the struts on October 4th 1999 led to a maximum displacement at the top of all longitudinal walls of approximately 1 mm. This behaviour was unexpected but it gave proof that the building reacts to propping.

Next, concrete beams of the foundation widening were placed in sections, firstly at the gable wall and subsequently at the choir wall. Therefore the existing foundations were alternately exposed to their base level over a maximum depth of 2.5m.

In the following step, the horizontal steel bracings were erected on the intermediate roof of the side aisle to prop the nave walls. The propping should stop the increase of inclination of the wall pillars.

Due to the large deformation of the northern wall the precondition for starting excavation work was the prestressing of the horizontal bracings. Even when the restoration work is carried out in stages, it further reduces temporarily the level of safety. Additional displacements are inevitable. During the construction phase from October 2000 to February 2001 at the northern wall, the settlements have increased to a maximum of approximately 6 mm in the middle between the choir and the gable wall. During that time the inclination of the northern wall increased by about 3 mm (fig. 10).

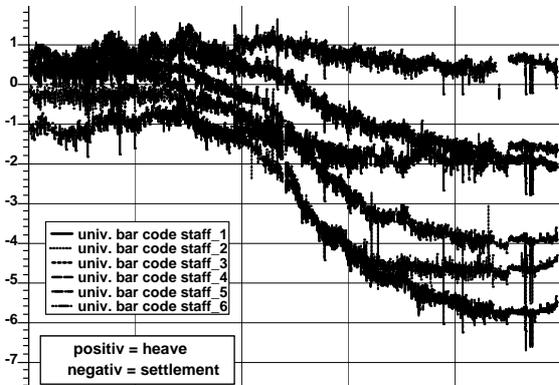


Figure 10. Settlement measurements northern wall

Altogether, settlements in the amount of +2mm (heave) and -6mm have been measured with the automatic levelling instruments by the end of restoration of the foundation in march 2001.

The inclination of the pillars was measured in the range of 1.3mm to 2.4mm towards the north. The prestressing of the horizontal bracings on September 1st 2000 resulted in displacements of approximately 2mm to 3mm in the southern direction and is equivalent to a change of inclination versus reference measurements made on July 1999. So far differential inclinations to a maximum of 8mm have been analysed with the pendulums. Typical measurements are shown in fig. 11 for pendulum P1 at the northern nave wall.

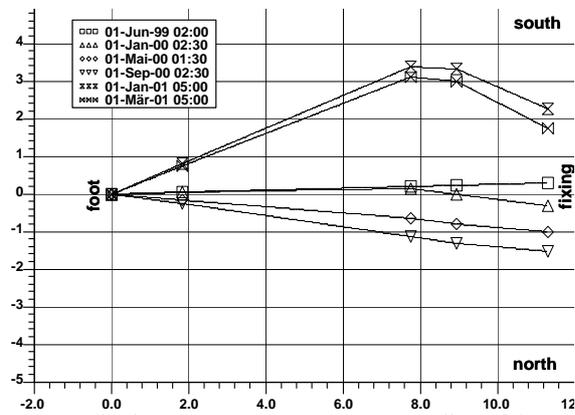


Figure 11. Inclination measurements northern nave wall, pendulum P1

The next import step of restoration is the reconstruction of the struts at the northern wall. This will be carried out at the end of March 2001. Further displacement is then expected and the inclination of the building will find a new starting point after restoration of the foundation.

The construction time for the execution of the foundation work was estimated at 8 month, but 18 month were needed up to the end in March 2001. The excavation work for the partial uncovering of the foundation took an enormous amount of time. It was also led by archaeologists from the office for historical monuments, who made interesting archaeological finds. From a contemporary point of view the planned renovation of the outer

and inner facades of Trinity Church will not begin sooner than one year after the completion of the restoration, accompanied by observation and measurements. In the meantime no further significant movement of the building should occur due to the first restoration stage of the foundations.

7 CONCLUSIONS

The behavior of historical buildings and their interaction with the subsoil remain often unknown, even if modern methods of investigation are used. Especially in such cases, the observational method is very helpful. Nevertheless it is absolutely necessary to be prepared for unknown reactions of the construction as well as the subsoil. The safety plan has to include a rapid time interpretation of measurements and response measures to prevent failure. This, as well as financial considerations, make a stepwise use of different restoration methods a necessity.

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